Portable sun tracking solar power kit

Research Paper

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Table of Contents

1 Introduction

1.1 Background to the study

Solar energy is energy received from the sun. It arrives in the form of light and other electromagnetic radiation which are converted into electrical energy. This is done using photovoltaic panels or concentrated solar power. Photovoltaic panels produce direct current (DC) as a result of the inherent photoelectric effect of the material used. This is the ability of matter to emit electrons when light shines on it.

Silicon is strongly affected by the photovoltaic effect. Photons, the particles of which light is constituted, hit the silicon atoms within the solar cell. These photons transfer their energy to the electrons within the silicon, causing them to escape the atoms' attractive fields. A charge imbalance is needed to cause these loose electrons to form an electrical current.

Two different types of silicon are used to create this imbalance. The different types of silicon are made by placing other elements amongst the silicon atoms and adding impurities, a process known as doping. These types are: n-type ("n" for negative), which has spare electrons, and p-type ("p" for positive), which is missing electrons. N-type silicon is usually produced by doping silicon with phosphorous. P-type silicon is usually produced by doping silicon with boron. This charge imbalance causes the electrons to flow from the n-type silicon to the p-type silicon, creating an electric field across the cell. This field directs the electrons into an electrical current.

At present, a dwelling can use solar generated electricity as a replacement for other electricity sources once the system is in place. A dwelling with enough photovoltaic panels and batteries for storage can render the dwelling energy-independent of the national grid.

This project focuses on sun tracking photovoltaic panels. Sun tracking panels are not a new concept. They are usually used on large solar farms as opposed to small scale solar power. Sun tracking is usually performed using precise, calculated and pre-programmed movements as opposed to real time tracking. Real time tracking requires determining the current position of the sun and adjusting the system based on this value.

Real time sun tracking can be used to create portable but efficient solar systems. At present most portable systems are not sun tracking. The existing systems that are sun tracking require a trailer to transport them. By using real time tracking we are able to decrease the size of the system while maintaining efficiency, therefore increasing portability.

Sun tracking benefits mostly during the morning and evening, when the sun is not perpendicularly overhead. This should be evident in any testing.

1.2 Objectives of this study

Solar-derived energy is often not used in applications well suited to its use. This is a cause for concern as the process of converting solar energy into electrical energy has no harmful impact on the environment. This renders solar power a favourable alternative in place of environmentally damaging energy sources.

Portable electricity is an area in which solar power can be greatly beneficial. As such, it is in humanity's best interests to create systems as efficient as possible.

Research revealed that having the solar panel directly facing the sun enables the panel to convert sunlight into electricity more efficiently and by a significant margin when compared to the relative performance of a stationary panel. This allows for small but efficient portable solar power systems.

The objective as such is to design and manufacture a portable power source that converts solar energy into electrical energy and can store excess energy. To minimize the size of the system, for the sake of portability, efficiency needs to be maximised.

1.3 Engineering Goals

The design requirements of this project are:

- The system must be portable.
- The system must be user friendly.
- The system must be able to store the excess energy.

The focus of the project was to achieve the engineering goals by means of solar tracking techniques. Specifically, it was not to produce a more efficient photovoltaic panel nor to test the efficiency of existing panels.

1.4 Scope

This project is focused on designing and producing a portable but efficient sun tracking solar power system with useful outputs. The intention is to improve the efficiency using only solar position tracking techniques. Specifically, it was not to produce a more efficient photovoltaic panel nor to test the efficiency of existing panels. As such, the intention is purely comparative in nature.

1.5 Plan of development

This document contains details on each progressive prototype. Three prototypes were produced in total. The project evaluation, testing and results can be found after the details of prototype 3, page 102 and onwards.

Each section details the mechanical, electrical and programming designs of each prototype. Testing, esults, evaluations and recommendations can also be found for each prototype.

2 Methodology

2.1 Prototype 1

2.1.1 Preliminary Design Procedure

2.1.1.1 Mechanical

In-depth research was done into sun tracking and as a direct result many ideas were borrowed from these researched plans. Two main designs were developed after multiple brainstorming sessions.
The two preliminary sketches are shown below:

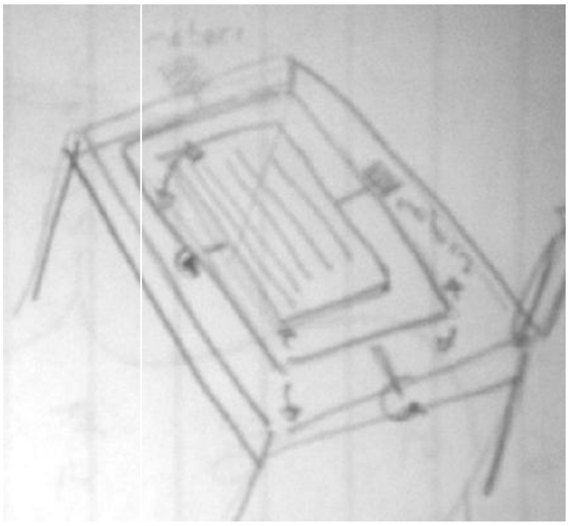


Figure 1: Prototype 1 Preliminary mechanical designs 1

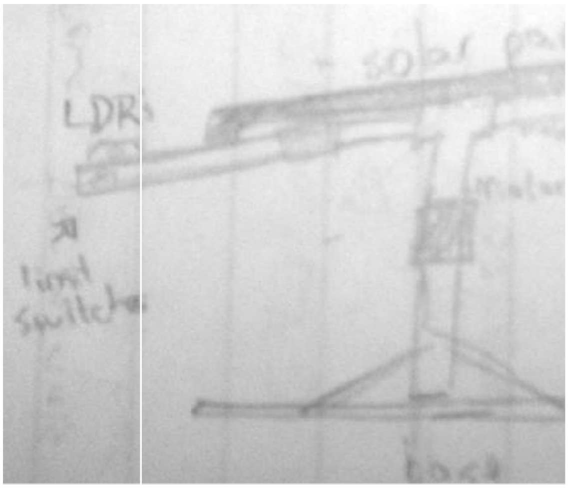


Figure 2: Prototype 1 Preliminary mechanical design 2

Notes on designs:

Design 1 (Figure 1)

This design would be difficult to construct as it involves many large moving parts. It would require precise construction using strong materials. These are both expensive and heavy, which in turn are both constraints for portability that need to be carefully controlled. It is a large design, it surrounds the photovoltaic panel. This would make it difficult to transport or pack. The design surrounds the photovoltaic panel and would therefore cast shadows across the photovoltaic panel. Due to the design of photovoltaic panels, even small shadows can completely disrupt power conversion. This would cause the design to be less efficient. The photovoltaic panel would be finely balanced, as the design uses a rotating gimbal within another allowing for 2 degrees of rotational freedom. This would make it easy for small motors or other mechanisms to angle the panel to face the sun perpendicularly. This would save energy, as less is used to track the sun.

Design 2 (Figure 2)

This design was designed with materials in mind. The main material that this design is intended to utilise is PVC piping. PVC pipes are light, strong and affordable. Using joints available on retail market, it would be feasible to create appropriate rotating joints. This is a fairly narrow based design, meaning that it may be physically unstable. The photovoltaic panel would be attached on top of the horizontal pipe this would cause the centre of gravity to be above the rotating centre of the pipe to which it is attached. This could cause issues related to motor strength, if it is difficult to rotate the panel. As the design rotates around its base the cables could become wrapped around the base, causing issues.

2.1.1.2 Electronic

It was decided that the design should not be tracking all the time. This requires less energy to run the circuitry and it prevents the panel from turning every time a shadow briefly covers a LDR. The system was able to rotate much faster than the apparent movement of the sun and thus the design needed a timer to enable and disable the tracking circuits at regular intervals.
For timing a simple 555 Integrated Circuit (IC) was used.

For the tracking component, a relatively simple electronic comparator circuit was made with a 339 Operational amplifier (Op-amp). This Op-amp compares two input values and outputs a current depending on which of the two has a higher voltage. The LM339 Op-amp has four separate comparators built into it. For the purpose of this prototype two Op-amps needed to be used for each of the two axes. Within each axis, both Op-amps would share the same inputs but the one would receive the input on the inverting input, while the other on the non-inverting input. The one Op-amp will trigger its output if the input is higher than a certain adjustable threshold, whereas the other Op-amp will trigger it's output if the same input is below a certain adjustable threshold voltage. The threshold values are made adjustable by means of potentiometers.

The Op-amps send their outputs to a motor driver chip, the L293D. The L293D chip has the ability to power two separate motor channels in both forward and reverse. The motor driver chip requires a directional input and an enable or power input for each motor channel, both of which the Op-amps provide. From the motor driver chip , the motors are wired up.

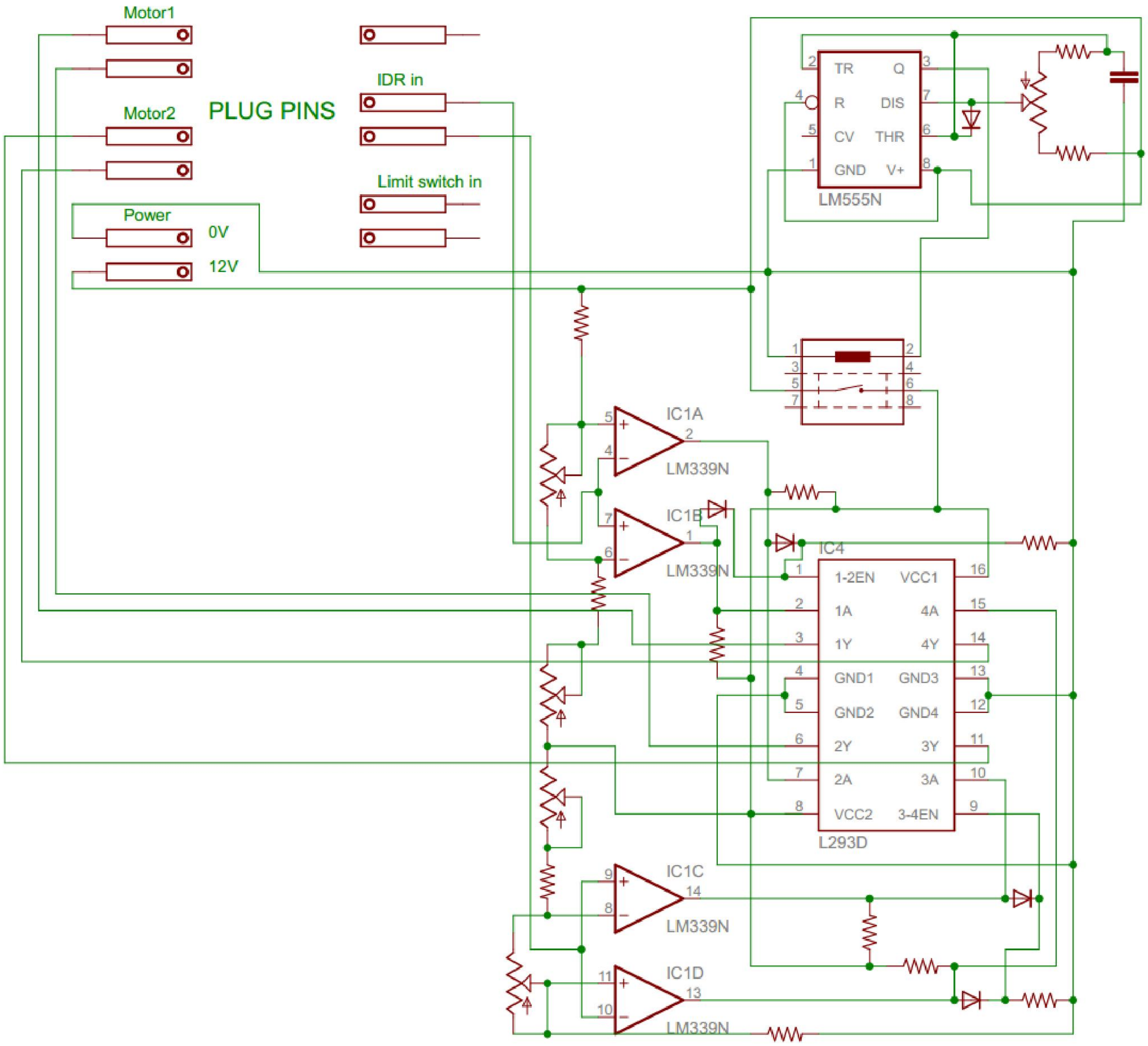


Figure 3: Prototype 1 Preliminary electronic design

2.1.2 Prototype 1 Development

2.1.2.1 Mechanical

The design was developed further and as a result the design grew more complex and specific.

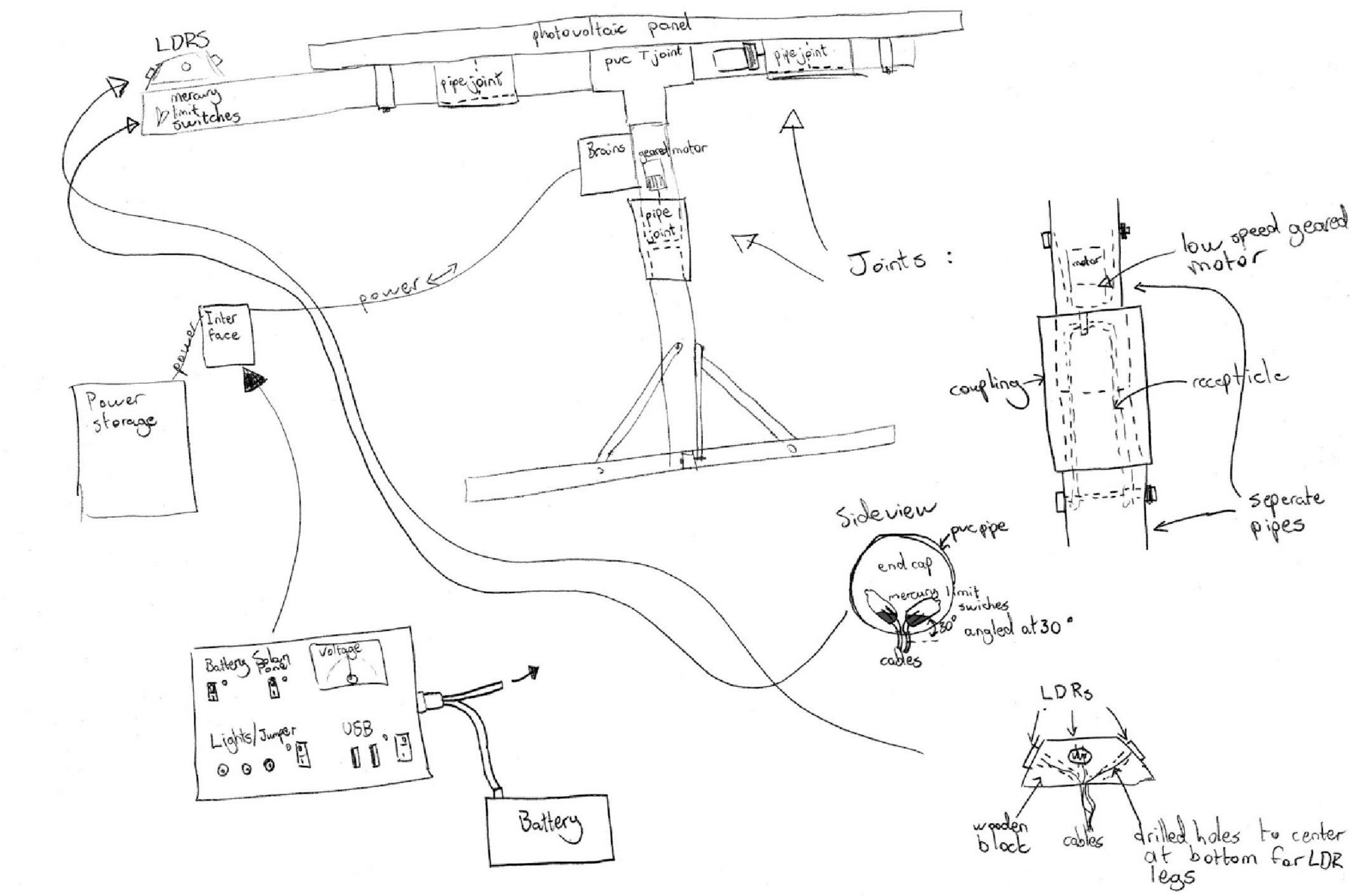


Figure 4: Prototype 1 Master Sketch

The conceptual sketch above briefly illustrates the main design features of the prototype. The sketch does not show any dimensions. Dimensions would be defined later.

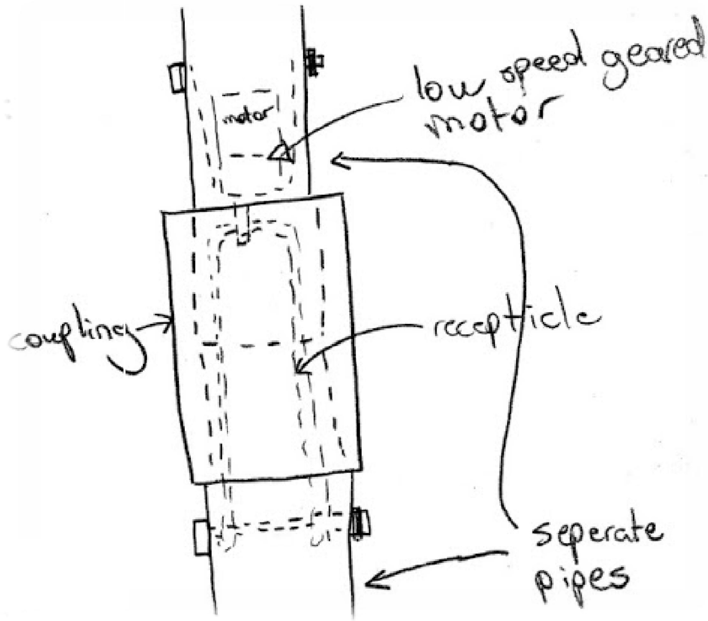


Figure 5: Prototype 1 Sketch of motorized rotating joints

There will be two such motorised rotating joints in the prototype.

One will be used to control the yaw or rotation around the base. The other will be used to tilt the photovoltaic panel. This combination allows for a full 360° range of tracking. The tilting rotational range will be restricted and therefore will not be able to do a full 360°. This should not hinder the power output, as the limited angles are unnecessary for tracking the sun in the sky.

The motor is mounted in the end of the one pipe by means of a bracket. This bracket would be mounted to the face of the gearbox and the bracket would have arms stretching back that are then bolted to the interior walls of the pipe.

The axle of the gearbox would be attached to a receptacle. This receptacle would also have arms stretching back that are then bolted to the interior walls of the other pipe.

The two pipes would be end to end, but inside a PVC coupling joint.

This coupling joint would fit tightly around the ends of both pipes. In order for both pipes to be able to rotate freely inside the coupling joint, they may need to be sanded around the ends to decrease the diameter slightly, in order to obtain a looser fit. Lubricant may also be necessary.

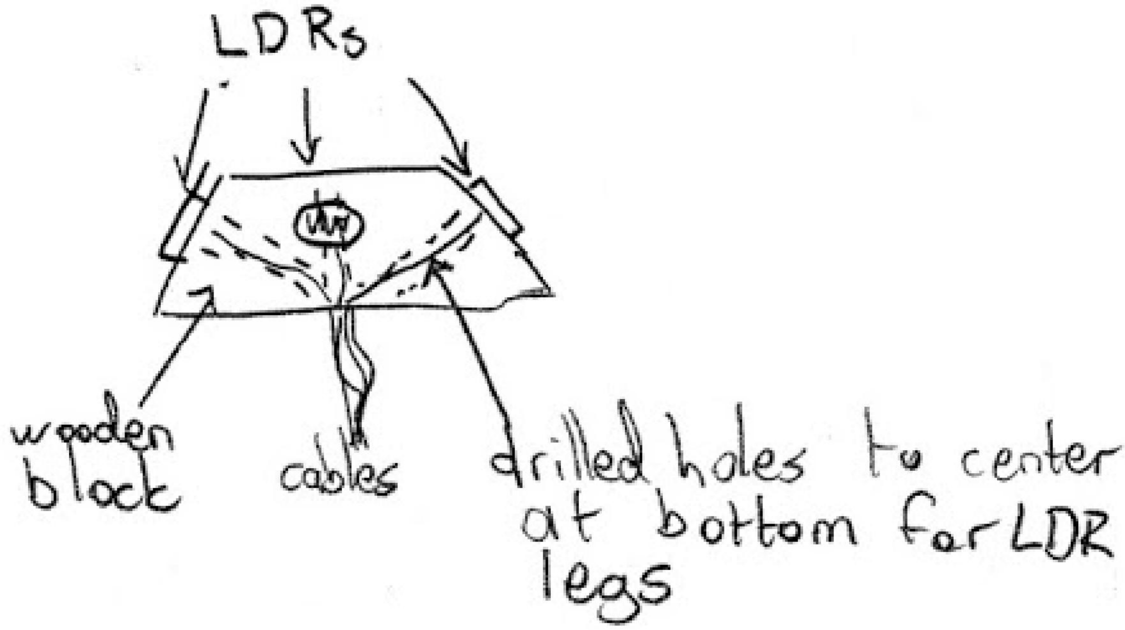


Figure 6: Prototype 1 Sketch of sensor block

The sensor block would be made out of a block of wood. This block would likely need to be cut into the rough shape with a saw, then sanded to the precise shape.
The block should have a truncated, square pyramidal shape.
The side faces should be at an angle of 45° in the vertical plane from the base of the block.
On each face of the pyramid, a LDR will be mounted. The LDRs will face perpendicular to the face they will be mounted on.
There should be a hole leading from the each of the faces to the bottom centre of the block. This would be for the cable from each of the respective LDRs.
The block will be wooden and would therefore need treatment to withstand the weather. This would likely include varnish and silicone sealant for the holes and the LDRs.

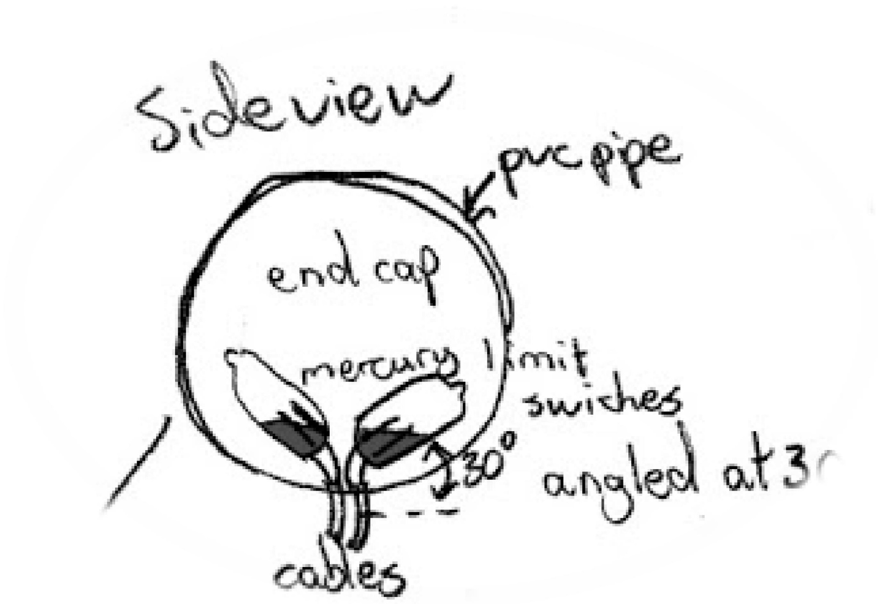


Figure 7: Prototype 1 Sketch of limit switches

In the end of the top, horizontal pipe there should be two tilt limit switches.

This top horizontal pipe is attached to the photovoltaic panel. This pipe tilts the photovoltaic panel. These switches will be for limiting the rotation.

Within the switches there are two pins and some conductive mercury. This causes the two pins to have an electrical connection when the mercury is touching both pins. This gives mercury switches the ability to disconnect the current when tilted at too great an angle.

Each mercury switch limits only one direction of rotation. As the pipe rotates in the one direction the one mercury switch will disconnect at a point, but only one. This will stop the motor from being able to rotate further in that direction, but not the other.

The switches would need to be mounted into a block of wood or alternatively, glued.

An end cap would need to cover the open end of the pipe. This would protect the exposed legs of the switches from weather like rainwater.

A clear end cap would be helpful for inspective purposes.

The angle of the switches will have to tuned to match the maximum rotational angles of the top pipe.

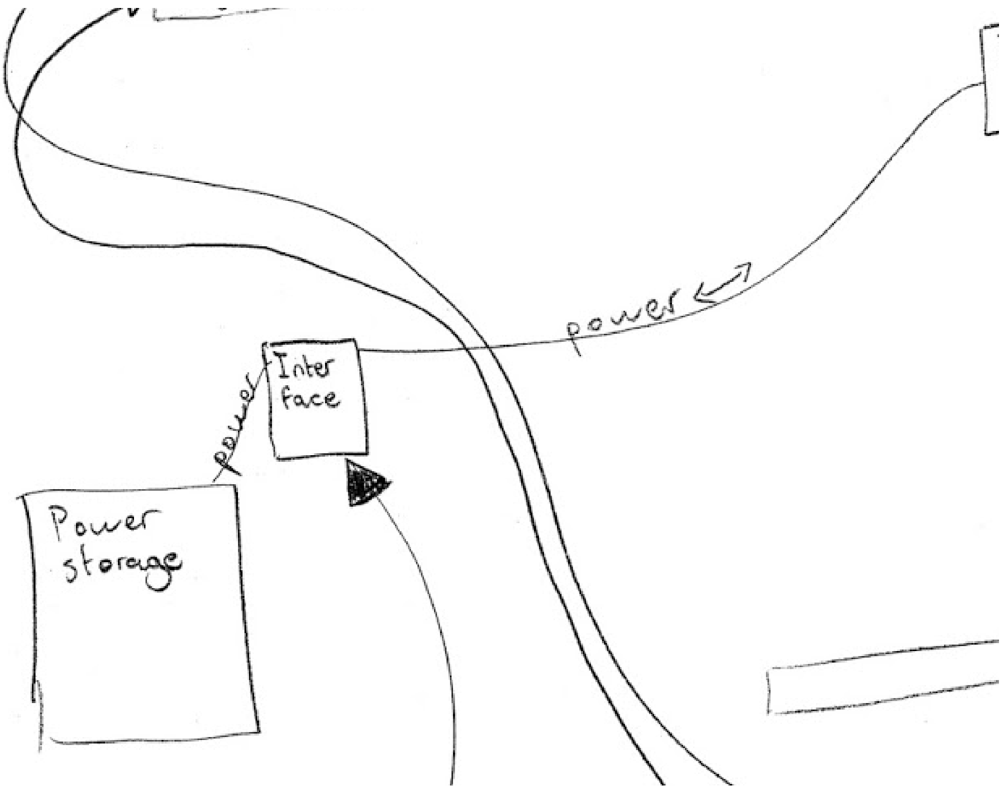


Figure 8: Prototype 1 Sketch of basic electronic overview

This is a brief electronic overview. The electronics will be shown in detail in the following chapter: 2.1.2.2 Electronic, pages 25 and onwards.

The plan is to have a small housing mounted to the vertical pipe of the prototype. This housing would contain all the logic circuits that would control the tracking of the sun.

A housing would be built to house the user interface. The user interface would contain all the useful outputs and necessary controls for the prototype.

Prototype 1 keeps the power storage separate from the interface and the physical sun-tracking device. This allows it to be easily disconnected and stored, replaced, externally charged or in use, to be packed out of the way.

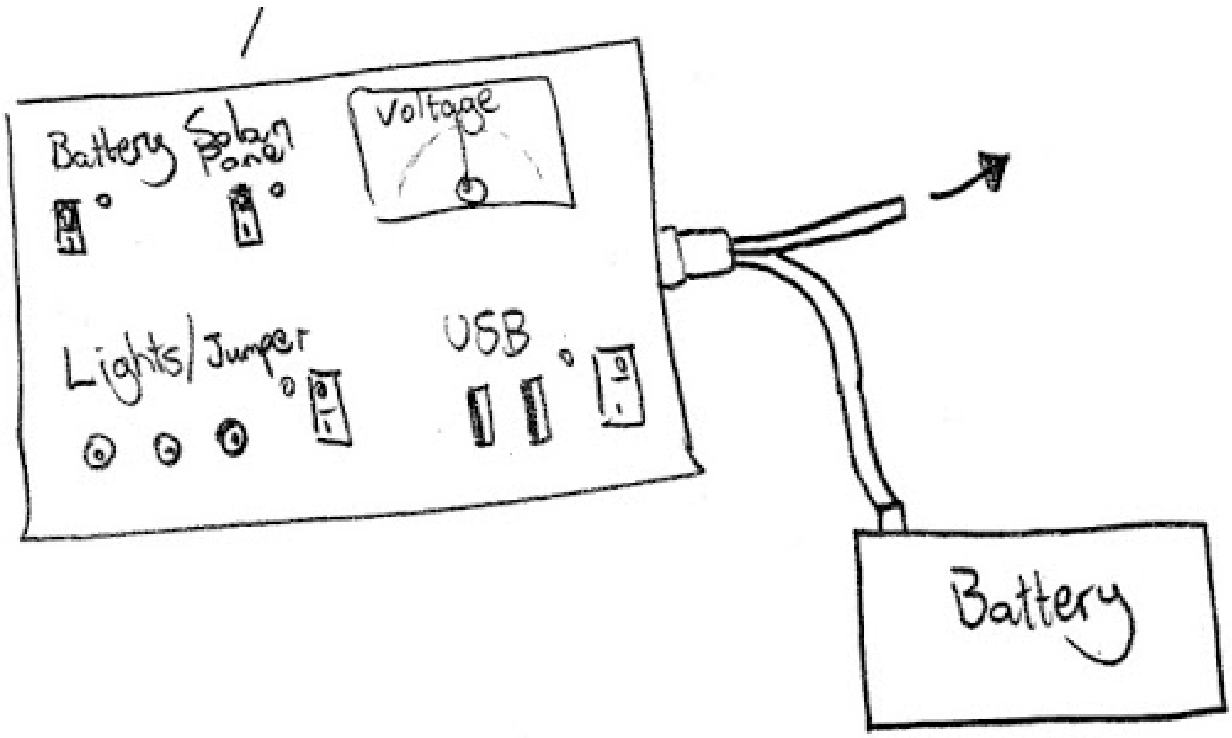


Figure 9: Prototype 1 Sketch of interface box and battery

The electronics will be shown in detail in the following chapter: 2.1.2.2 Electronic.

A housing would be built to house the user interface. The user interface would contain all the useful outputs and necessary controls for the prototype.

The interface will include the following:

- A switch to connect or disconnect the battery. There will also be an LED to indicate power.
- A switch to connect or disconnect the tracking electronics. There will also be an LED to indicate power.
- A switch to power the ports for lights or jumper. There will also be an LED to indicate power.
- A switch to power the regulated USB outputs. There will also be an LED to indicate power.
- A potentiometer showing the voltage of the common power rail.

Prototype 1 keeps the battery separate.

The following resources are required to construct Prototype 1. This list does not include the required electrical components:

- PVC pipes
- 3 x pipe joins
- 1 x T-junction
- PVC plastic sheet
- 100x50x100 hardwood board
- 10x3 aluminium bar
- 13x13 aluminium bar
- 31x M6 bolts
- 31x M6 nuts
- 3x M6 screws
- Plastic grease
- Nut lock
- 1 x solar panel
- Silicone waterproofing gel
- Waterproof panel box

The construction process of Prototype 1 can be found below. For measurements please refer to the technical drawings under the heading Final Design, Mechanical:

- Gather the required materials.
- Cut PVC pipes to appropriate length.
- Cut aluminium profiles to appropriate lengths.
- Drill holes in correct places on pipes.
- Drill holes in correct places on aluminium pieces.
- Bolt aluminium together and then to the PVC pipes to construct the base.
- Fit coupling pieces over the ends of the pipes.
- Sand the ends of the pipes so that they can rotate freely.
- Construct motor brackets and receptacles out of aluminium.
    - Drill hole in motor receptacle for gearbox axle.
    - Drill a perpendicular locking hole.
    - Tap the hole and screw in bolt to lock in axle.
- Attach motor bracket to the face of the gearbox.
- Fix the bracket with the motor to the inside of the pipe.
- Fix T-joint to the top of the vertical pipe.
- Fix two horizontal pipes to the T-joint.
- Fix the second motor and motor bracket into the end of the one pipe.
- Attach the matching motor receptacle to the inside of the outer horizontal pipe.
- Attach the outer horizontal pipes to the photovoltaic panel.
- Do this by bending aluminium profile over the pips and bolting the ends to the panel.
- The middle part that is bent over the pipe has a hole drilled in and is also bolted.
- Construct the wooden sensor block.

    - Cut out the basic shape from a block of wood.
    - Sand it down to the perfect shape.
    - Drill holes from the centres of the faces to the bottom centre.
    - Insulate LDR legs then glue the LDRs into the sensor block.
- Attach the sensor block to the top of the protruding horizontal pipe.
- Construct the limit switch block.
    - Cut the basic shape out of a block of wood.
    - Drill holes for the legs
- Attach the limit switch block inside the end of the protruding horizontal pipe.
- Attach receptacles to the correct gearboxes.
- Completely disassemble.
- Solder cables to all necessary electronic components.
- Run cables to the centre of the vertical pipe.
- Glue necessary loose components or exposed electronic components.
- Re-assemble.
- Attach box with all controlling electronic the side of the vertical pipe.
- Run cables to the interface box.
- Construct interface box.
    - Use a panel-mounted box
    - Cut holes into the lid for components to fit.
    - Insert components.
    - Glue if necessary.
    - Solder wires to the legs of the components.
    - Attach wires to appropriate circuits.
    - Screw in the lid.

Below are some photos that were taken during the construction process:

Figure 10: Prototype 1 Base

Figure 11: Prototype 1 The beginnings of a motor bracket

Figure 12: Prototype 1 Motor Bracket

Figure 13: Prototype 1 Motor Bracket and motor inside pipe

Figure 14: Prototype 1 The beginnings of the motor receptacle

Figure 15: Prototype 1 Motor receptacle


Figure 16: Prototype 1 The finished motor brackets and receptacles


Figure 17: Prototype 1 The horizontal pipes and T joint

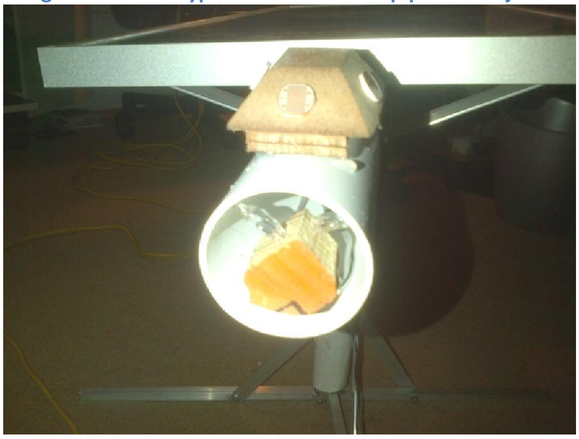


Figure 18: Prototype 1 Close up of the attached sensor block and limit switches

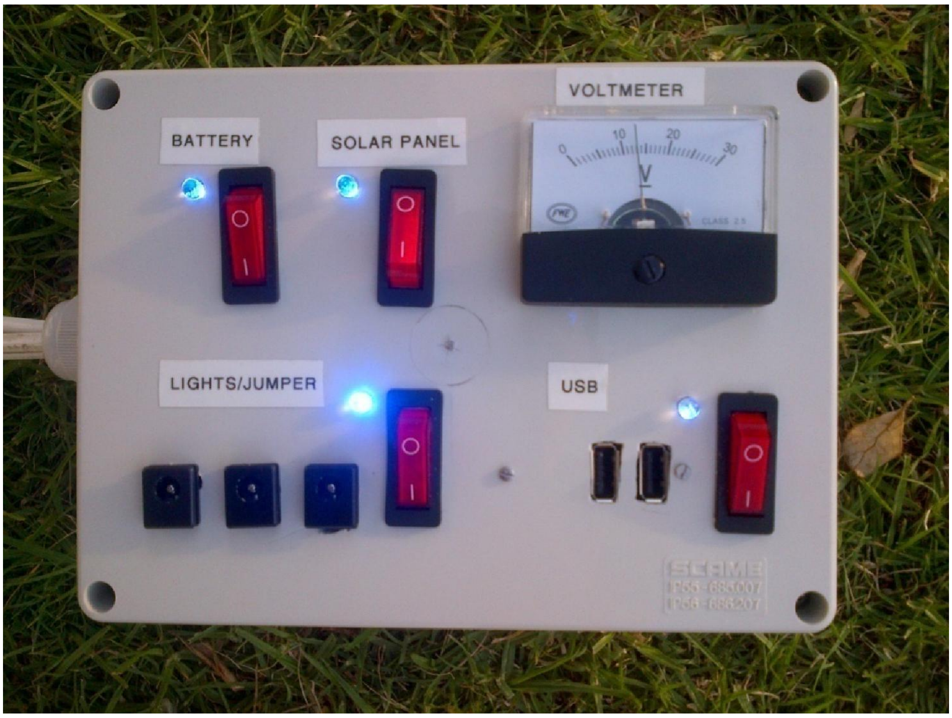


Figure 19: Prototype 1 Interface Box

Figure 20: Prototype 1 Semi-constructed and in preliminary testing

2.1.2.2 Electronic

The original plan was to make logic circuits to handle the solar tracking.

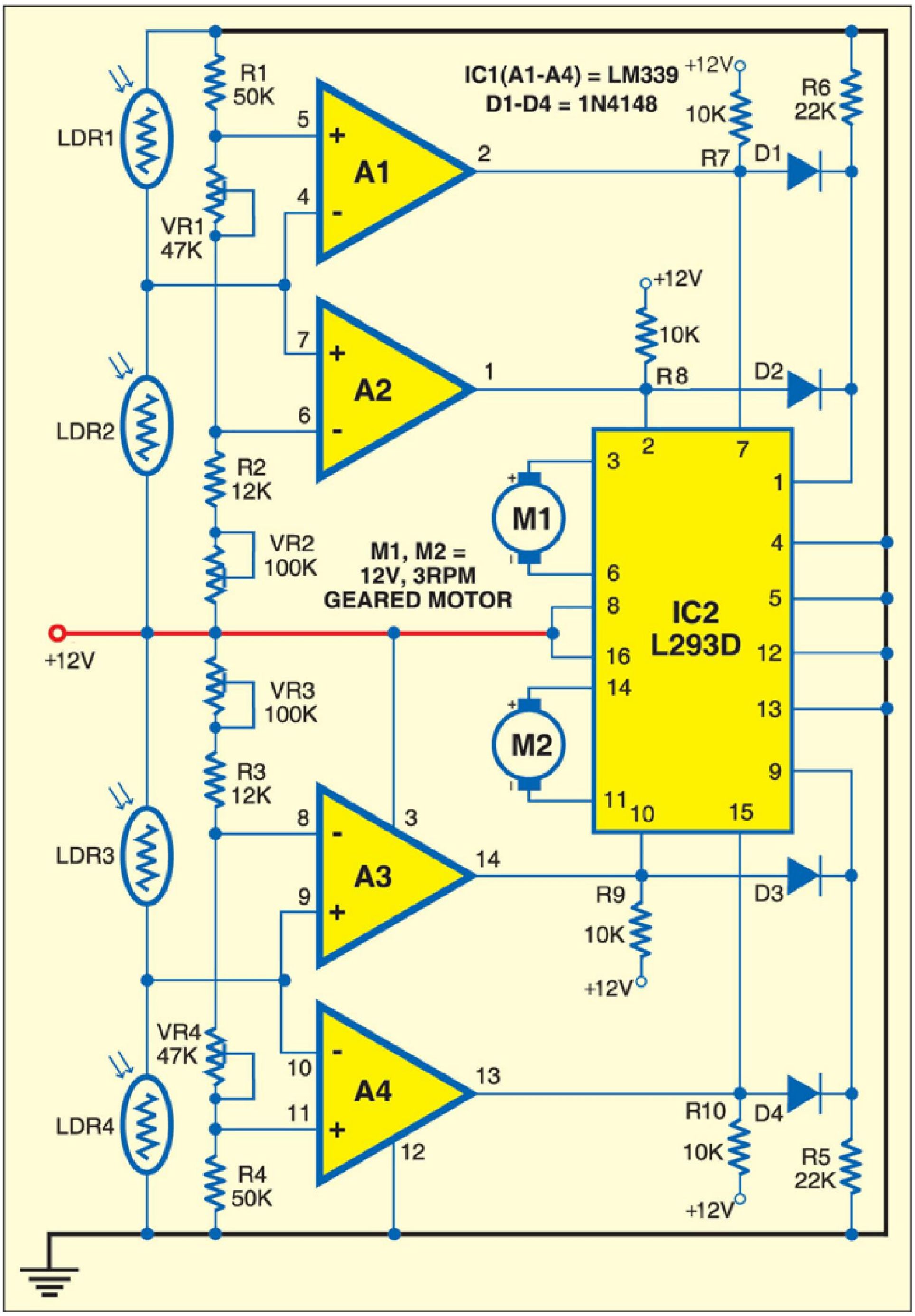


Figure 21: Prototype 1 Original electronic logic circuit schematic

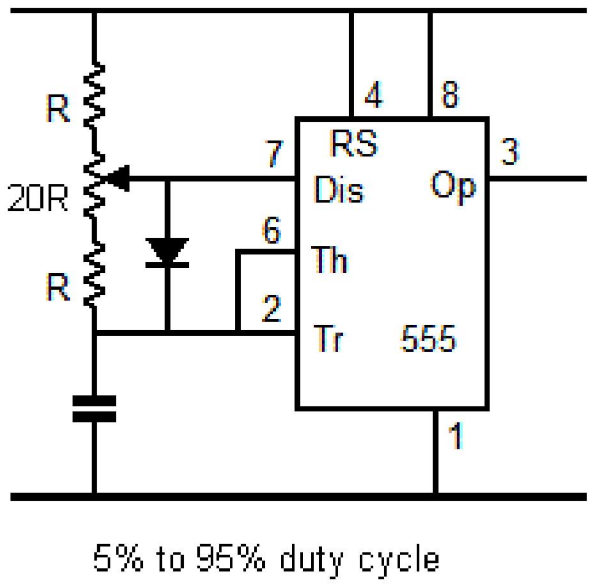


Figure 22: Prototype 1 Original electronic timing schematic

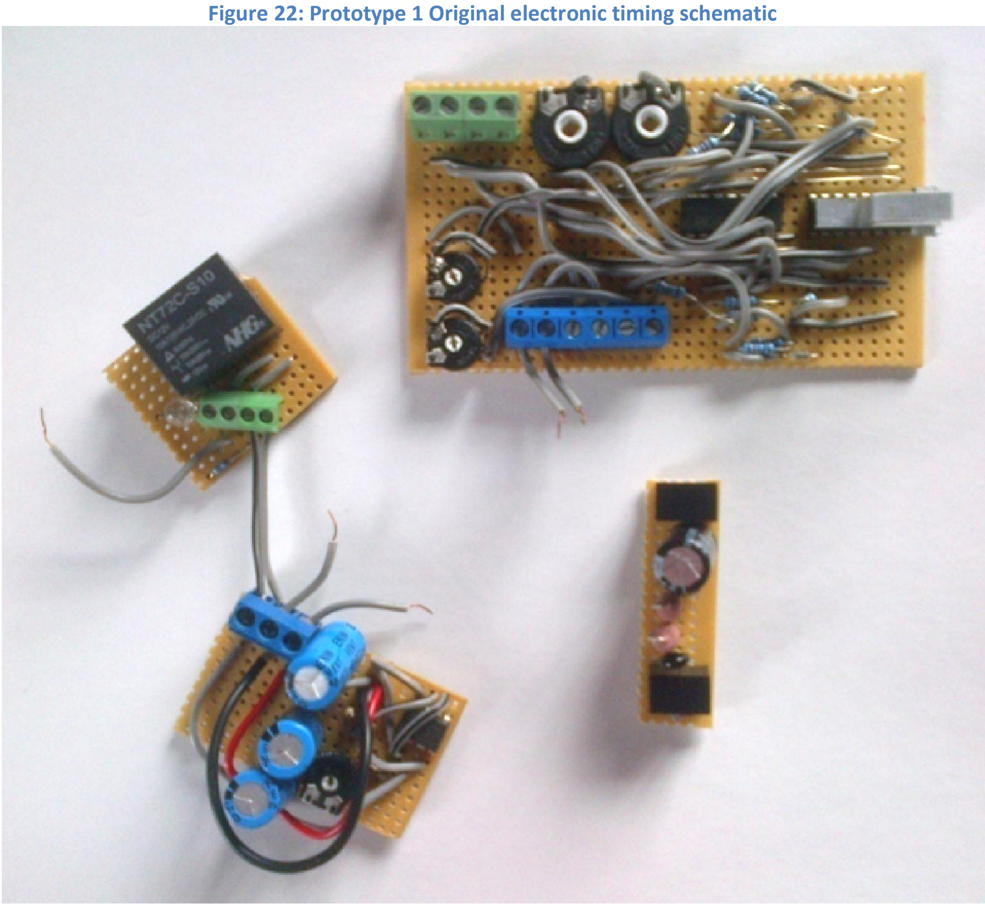


Figure 23: Prototype 1 Original electronic logic circuits

During this construction process a number of problems has to be dealt with. The electronic logic circuits did not work as intended. A great amount of time was spent on troubleshooting the circuits, but the other problems remained:

Getting the timing of the timing circuit correct proved to be challenging and many large capacitors had to be used in order to get the slow timing that was required. After testing multiple capacitor combinations this circuit was made fully functional.
After testing the motor driver circuit it was soon discovered that the motor driver chip did not have sufficient power to drive both motors. This would have to be upgraded to a more powerful chip.
Before this upgrade, a major flaw in the motor driver circuit was discovered. The motor driver cannot function properly if the motor direction changes instantly and there is no delay between the directional input and the enable input. This delay is required for the chip to work properly. To add in a small delay like this would be very challenging and would take up too much of the little space that the circuits had.
The circuit was discussed with an electronics and programming professional, Theo Keyzer. His opinion backed up the findings that in order for the circuit to work as intended it needed a more powerful motor driver, capable of handling higher voltages and current. A delay also needed to be introduced between the enable pin and any change in direction.
The issues with the various electronic circuits were discussed further and it was discovered that there was a circuit board in production that was perfect for the needs of this project. It had a motor driver multiple tiers more powerful than the original motor driver. The only major difference in terms of this production circuit is that this board had a programmable IC on it.

It was concluded that the switch to the new circuit board had to be made. It was tidier and gave much more room for tweaks to be made. It also contained the higher power motor driver chip, which was needed to power the motors.

New circuits had to be developed for the system to operate with the new circuit board.

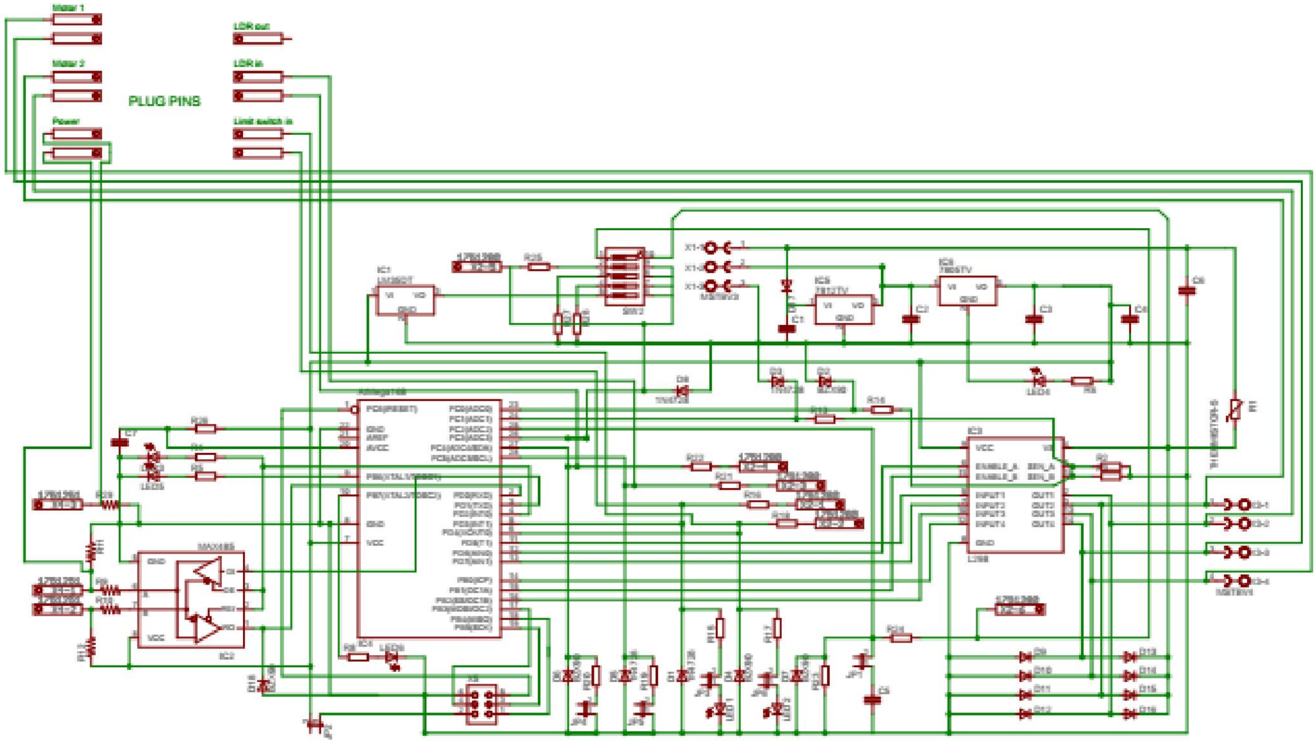


Figure 24: Prototype 1 Programmable Motor Driver circuit schematic

Note:
Plug pins is a reference to the socket pins of the circuit board. The pins plugged into a socket which was mounted to the vertical pipe and was directly connected to all the electronics.

In order to connect the electronics on the prototype and the electronics in the interface box, a long cable had to be made. Near the prototype a small in-line plug was put in the cable, for ease of packing and transporting.

A power switch was made to enable or disable the tracking capabilities.

A small 12 V regulator was put in line before the LDRs. This was ensure a constant voltage input. This was because the photovoltaic panel had the ability to change the voltage. The sensors readings were skewed as a result of these voltage fluctuations. All the electronics on the prototype were routed to the single, multi-pin socket. This socket was where the motor driver board would plug in.

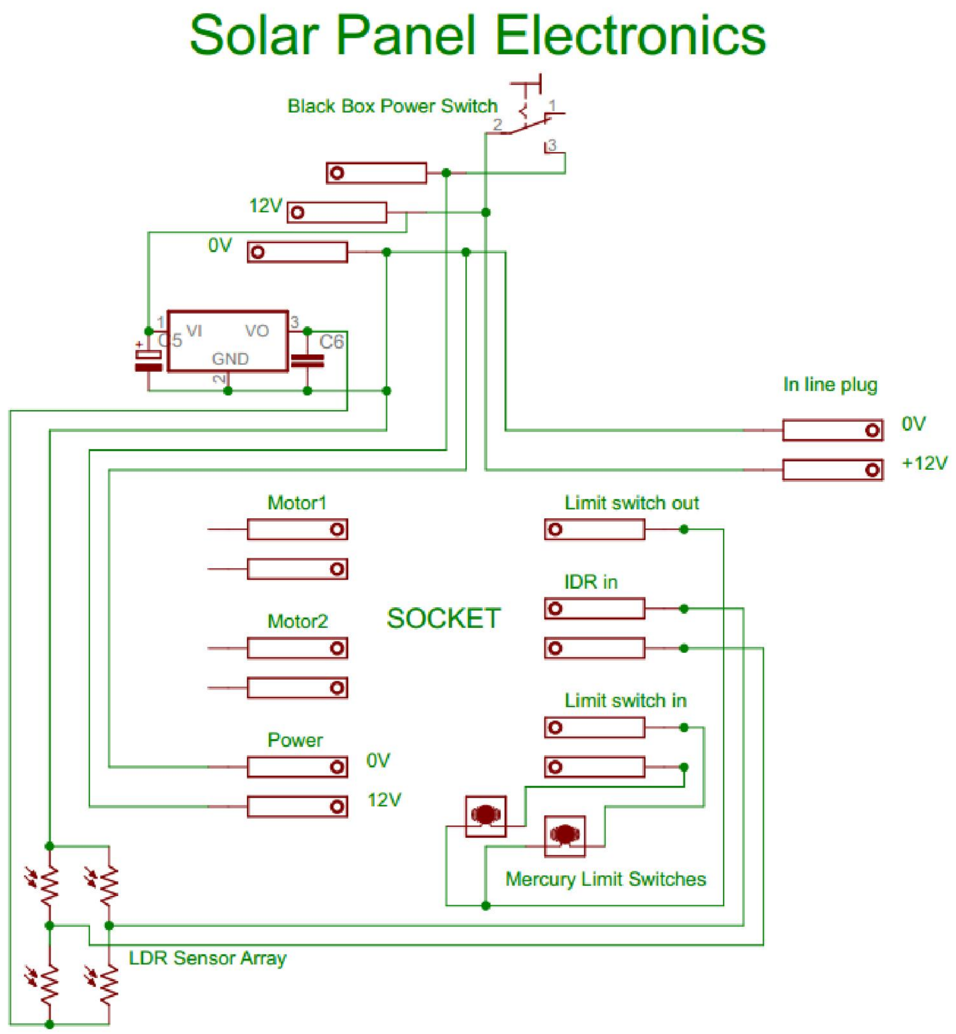


Figure 25: Prototype 1 On-board electronics

A 5 V regulator was put in line before the USB outputs. This was to ensure that the voltage output from the USB ports were always constant. USB ports are universally 5 V and this was a necessity for a charging port.

A 12 V regulator was put in line before the light outputs. This is order to maintain a constant 12 V. The lights that were used would get very hot if the voltage was any higher than 12 V.

A simple switch and indicative LED with a resistor was put at each output to easily control outputs and monitor activity.

The jumper output is a direct connection to the battery and the photovoltaic panel. This would be used for charging other 12 V batteries or simply powering 12 V devices.

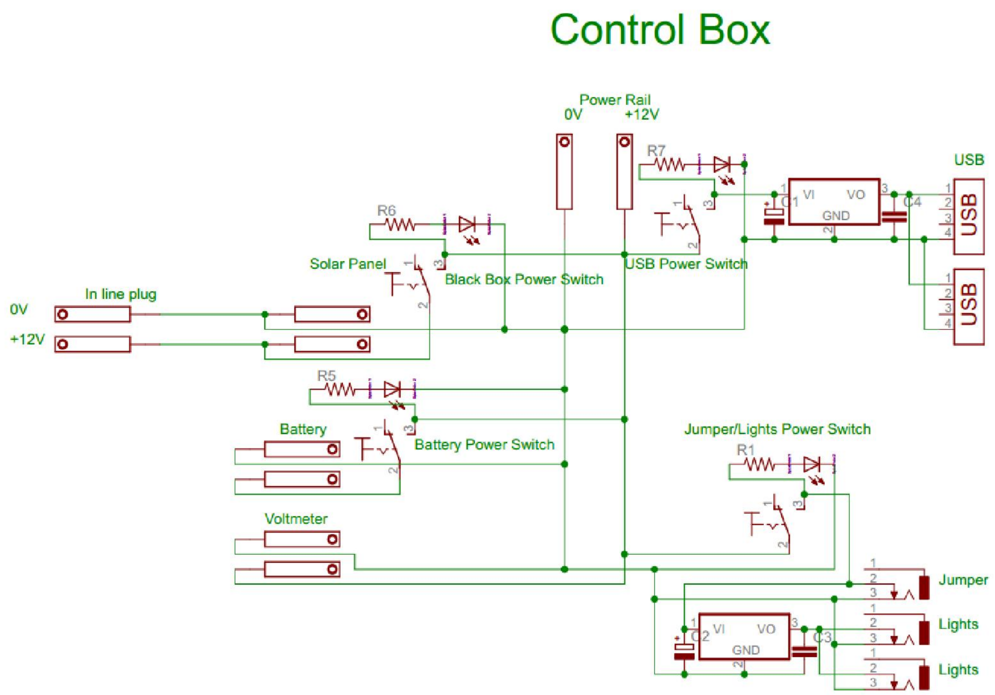


Figure 26: Prototype 1 Interface Box electronics

The above circuits were constructed. The parts list is shown below:

Electronics Part List:

- 2 x 12v 450mA 13 rpm motor
- 1 x 12v 40Ah car battery
- 4 x LDR 2kΩ 35v
- Electrical wire solid core copper
- 5x switch 200W
- Voltmeter 0-30v
- 2x USB port
- 4x DC power plug
- 4x DC power socket
- 1x 2,2kΩ resistor 1/4W
- 3x 1kΩ resistor 1/4W
- 4x 5mm Clear Blue LED
- 2x Mercury limit switch
- 2x 7812 12v 1A regulator
- 1x 7805 5v 1A regulator
- 3x 0,1µF 20v tantalum capacitor
- 3x 470µF 16v electrolytic capacitor
- 1x Driver87 board
- 1x AtMega168
- 3x 470µF 16v electrolytic capacitor
- 1x Driver87 board
- 1x AtMega168

Photos of the circuits are shown below:

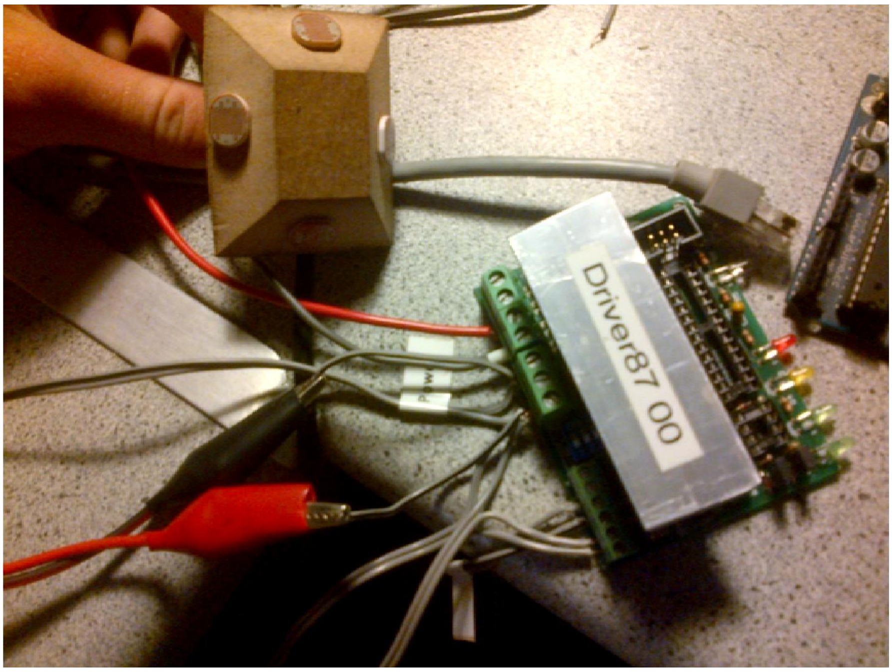


Figure 27: Prototype 1 Motor Driver circuit shown exposed with sensor block

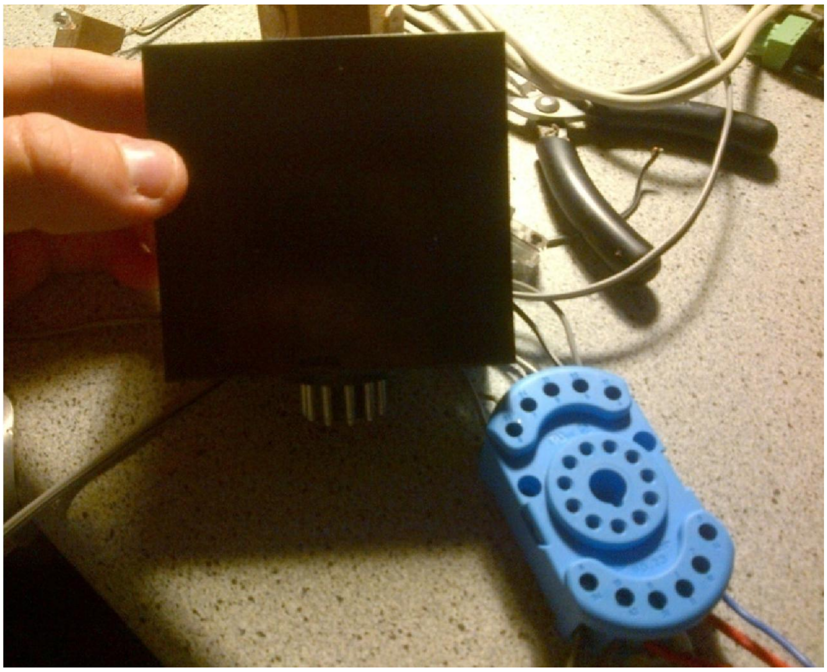


Figure 28: Prototype 1 Motor Driver circuit housing and socket

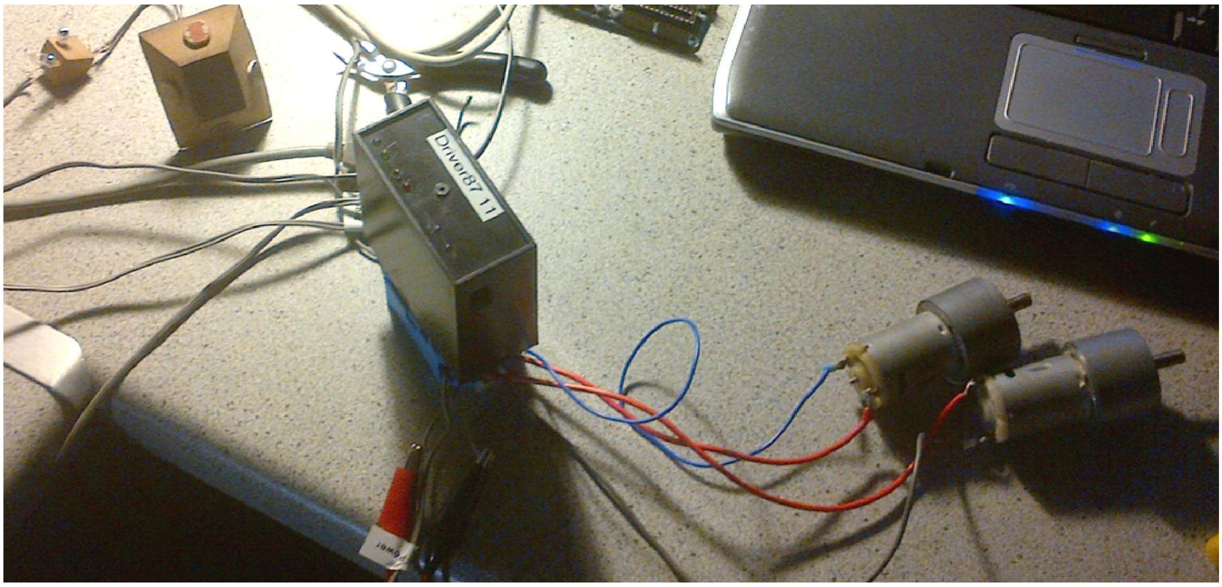


Figure 29: Prototype 1 Complete electronic tracking setup in intermediate testing

2.1.2.3 Programmed

The programmable IC in the Driver87 board is compatible with an easily available hobbyist PC-on-a-board and is programmable via USB ports. This became the new centre of the system. With some programming the effects of the simple logic circuit were emulated. Being programmable made it much easier to make timing changes, add delays and add preventative measures.
The program had to follow a certain logical pattern.

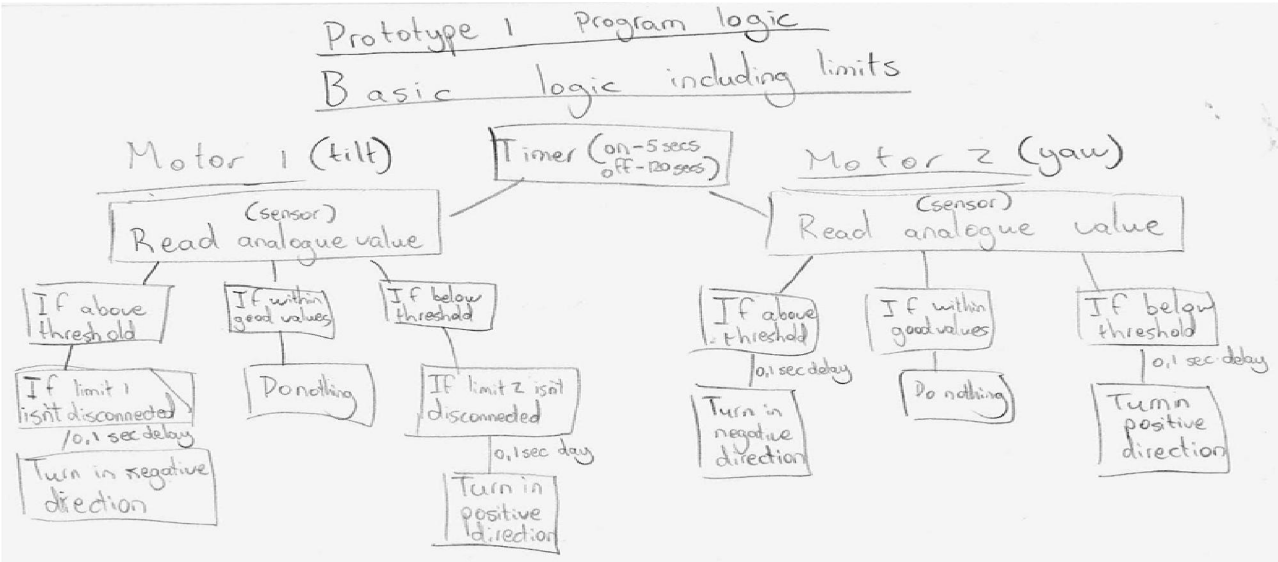


Figure 30: Prototype 1 Program logic sketch

After this sketch the program development was initiated.

The first steps were defining pins on the chip. The pins had to be matched to the appropriate inputs or outputs.

The next steps were reading values from the input pins and writing values to the outputs pins.
Next, the logic had to be implemented.

To program the chip used in the motor driver circuit board, the programmable PC-on-a-board had to be used.

The programmable PC-on-a-board was plugged into a computer with the USB cable.

The computer was used to program the chip using an open source hobbyist programming language.

The chip was removed from the motor driver board and placed in the programmable board and then the program from the computer could be downloaded.

The chip would then be removed and put back in the motor driver board.

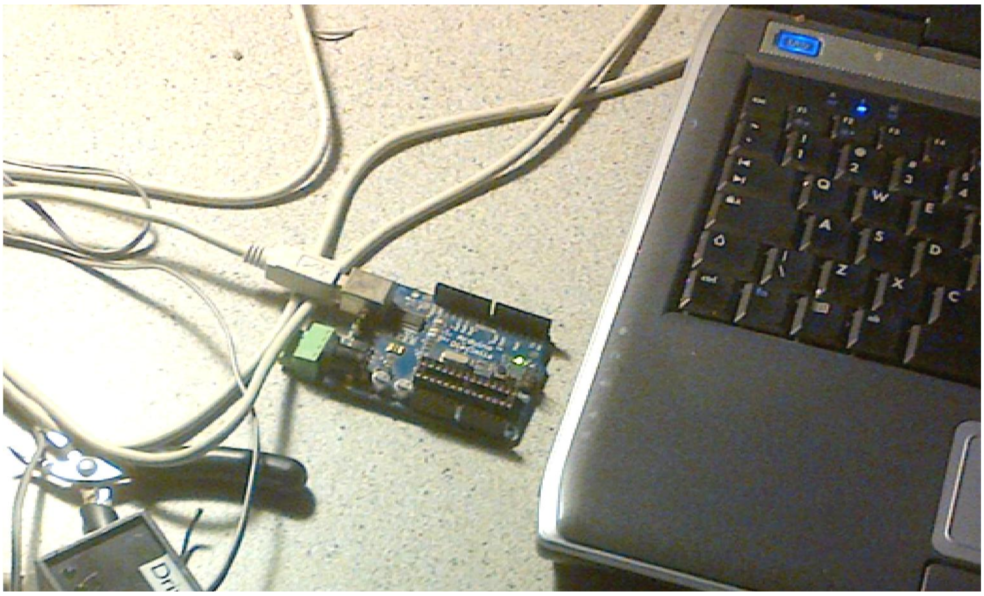


Figure 31: Prototype 1 Programmable hobbyist computer board used to program the chip

2.1.3 Prototype 1 Final Design

2.1.3.1 Mechanical Computer-Aided Design (CAD) drawings

See below the following photos of the complete prototype:

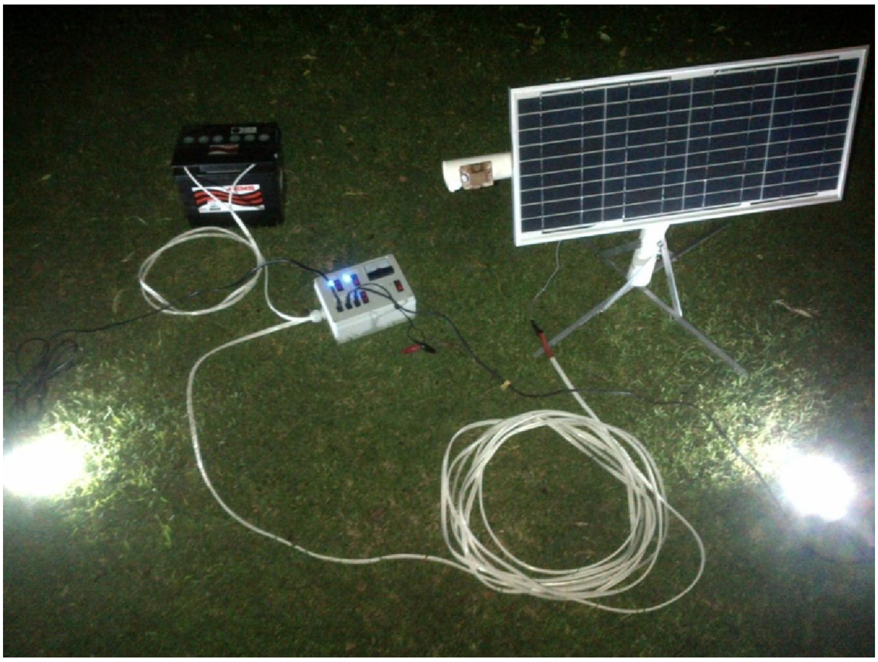


Figure 32: Prototype 1 Complete Photo

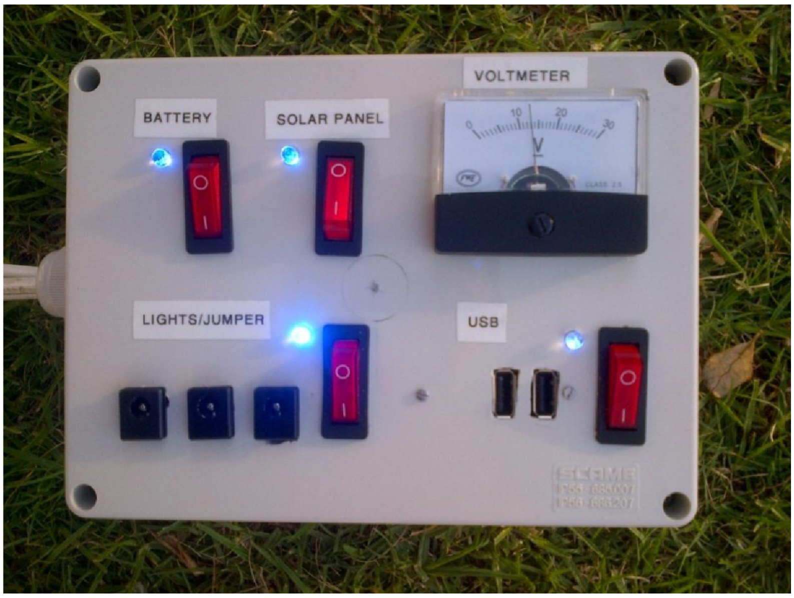
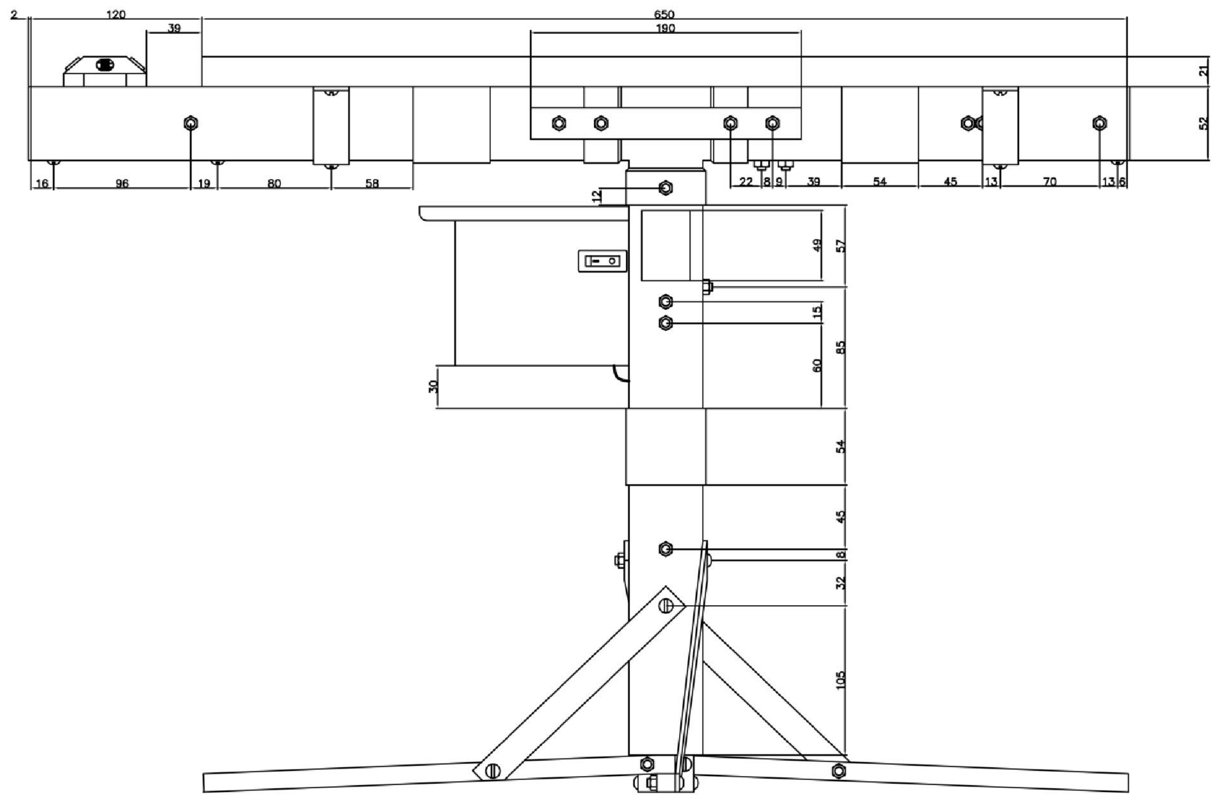


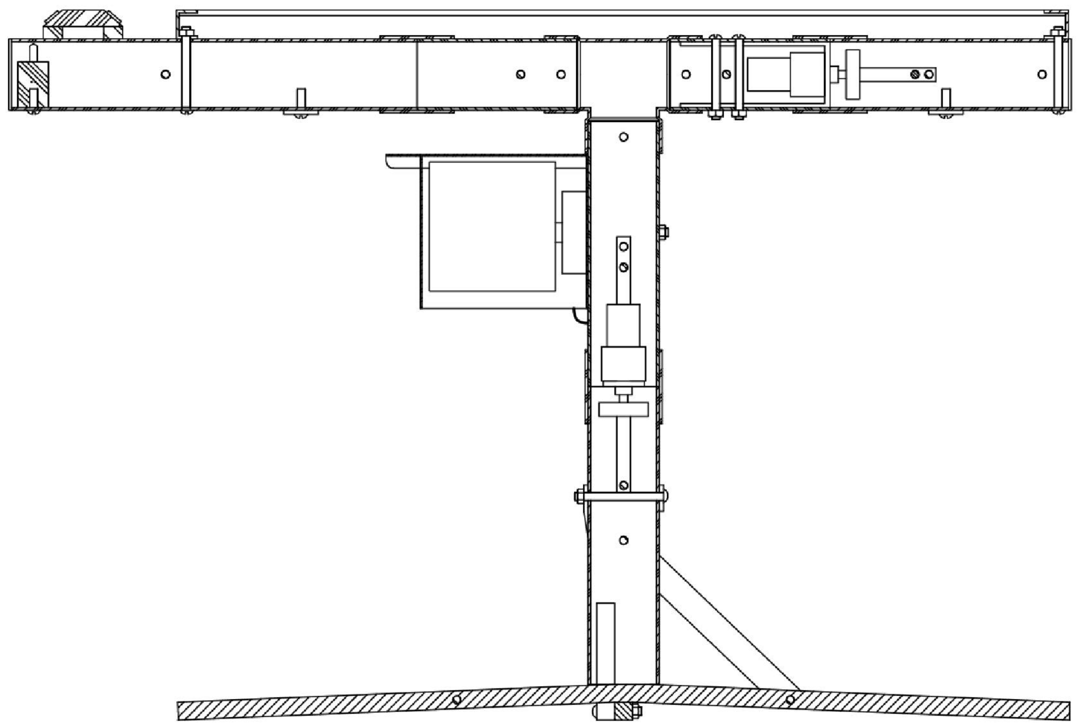
Figure 33: Prototype 1 Finished Interface box

For details and measurements regarding construction, please see the technical drawings on the following pages:



NOTES:
ALL BOLTS AND NUTS M6 UNLESS OTHERWISE SPECIFIED
ALL ALUMINIUM BARS ARE 10X3 UNLESS OTHERWISE SPECIFIED
FOR DETAILS OF SMALLER COMPONENTS SEE AUXILIARY DRAWINGS PAGE
ALL PIPE JOINS ARE Ø56 X54

DRAWING NAME FULL_STRUCTURE_ASSEMBLED	
FILE NAME SCIENCE_FAIR_2014.DWG	
DRAWING NUMBER SF14-3	DRAWN BY J.SENIOR
	SCALE 1:4
DRAWN 02/05/2014	PRINTED 03/05/2014



NOTES:
ALL BOLTS AND NUTS M6 UNLESS OTHERWISE SPECIFIED
ALL ALUMINIUM BARS ARE 10X3 UNLESS OTHERWISE SPECIFIED
FOR DETAILS OF SMALLER COMPONENTS SEE AUXILIARY DRAWINGS PAGE
ALL PIPE JOINS ARE Ø56 X54

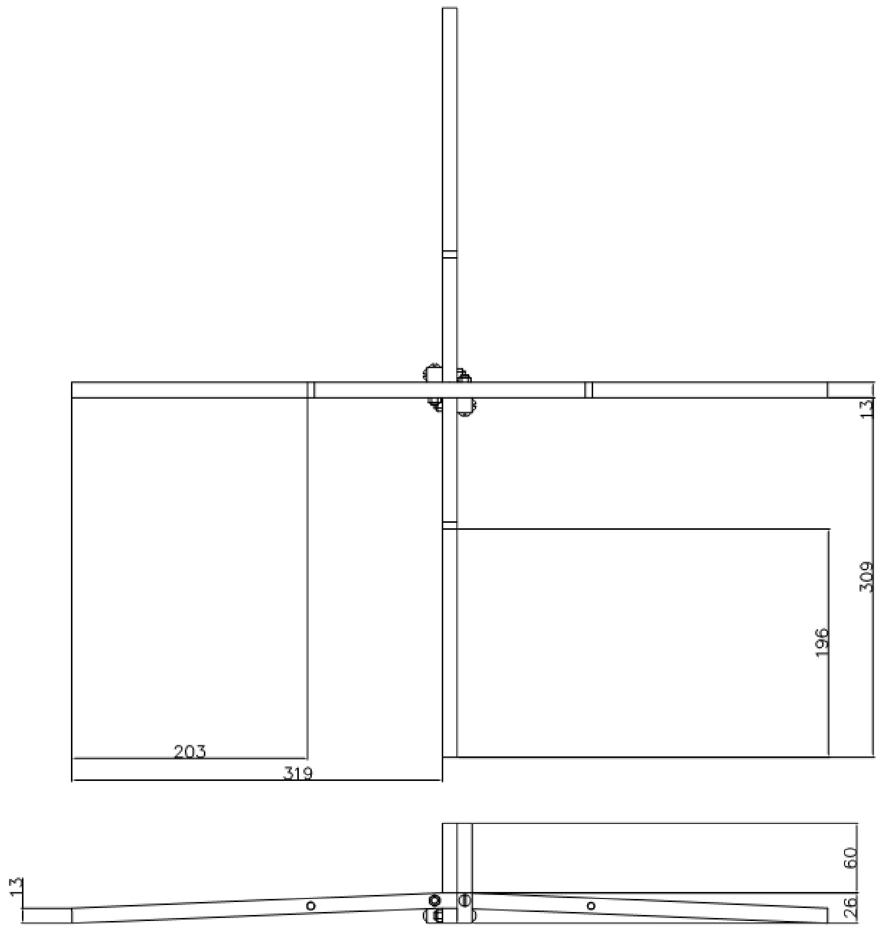
HATCHING LEGEND

PVC

ALUMINIUM

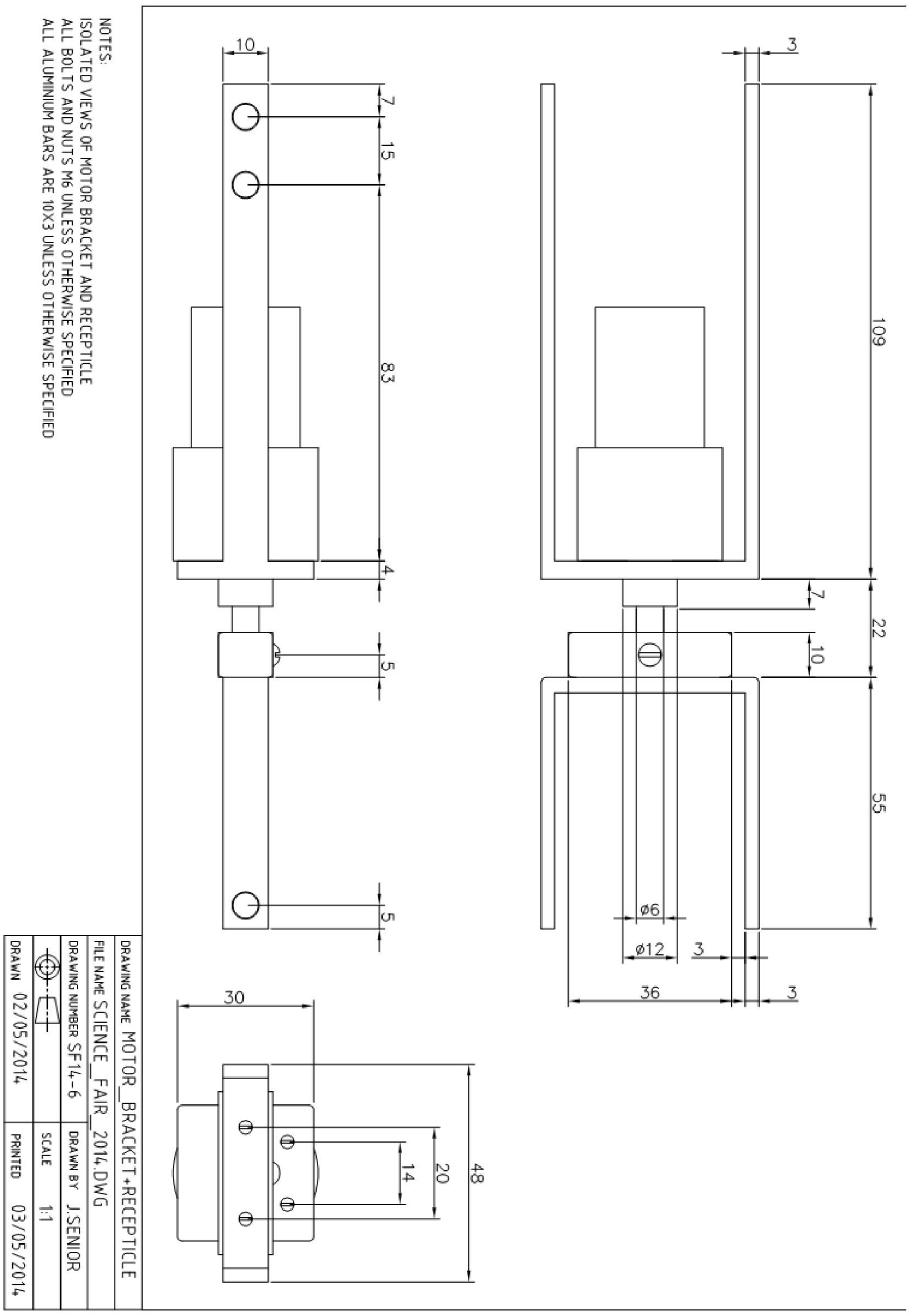
WOOD

DRAWING NAME SECTIONAL_OF_STRUCTURE	
FILE NAME SCIENCE_FAIR_2014.DWG	
DRAWING NUMBER SF14-4	DRAWN BY J.SENIOR
	SCALE 1:4
DRAWN 02/05/2014	PRINTED 03/05/2014



ES:
.ATED TOP AND SIDE VIEW OF SOLAR PANEL BASE SUPPORT
BOLTS AND NUTS M6 UNLESS OTHERWISE SPECIFIED
ALUMINIUM BARS ARE 10X3 UNLESS OTHERWISE SPECIFIED

DRAWING NAME SOLAR__PANEL__BASE	
FILE NAME SCIENCE__FAIR__2014.DWG	
DRAWING NUMBER SF14-8	DRAWN BY J.SENIOR
	SCALE 1:5
DRAWN 02/05/2014	PRINTED 03/05/2


NOTES:
ISOLATED VIEWS OF MOTOR BRACKET AND RECEPTICLE
ALL BOLTS AND NUTS M6 UNLESS OTHERWISE SPECIFIED
ALL ALUMINIUM BARS ARE 10X3 UNLESS OTHERWISE SPECIFIED
DRAWING NAME MOTOR_BRACKET+RECEPTICLE
FILE NAME SCIENCE_FAIR_2014.DWG
DRAWING NUMBER SF14-6
DRAWN BY J.SENIOR
SCALE 1:1
DRAWN 02/05/2014
PRINTED 03/05/2014
10
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ø12
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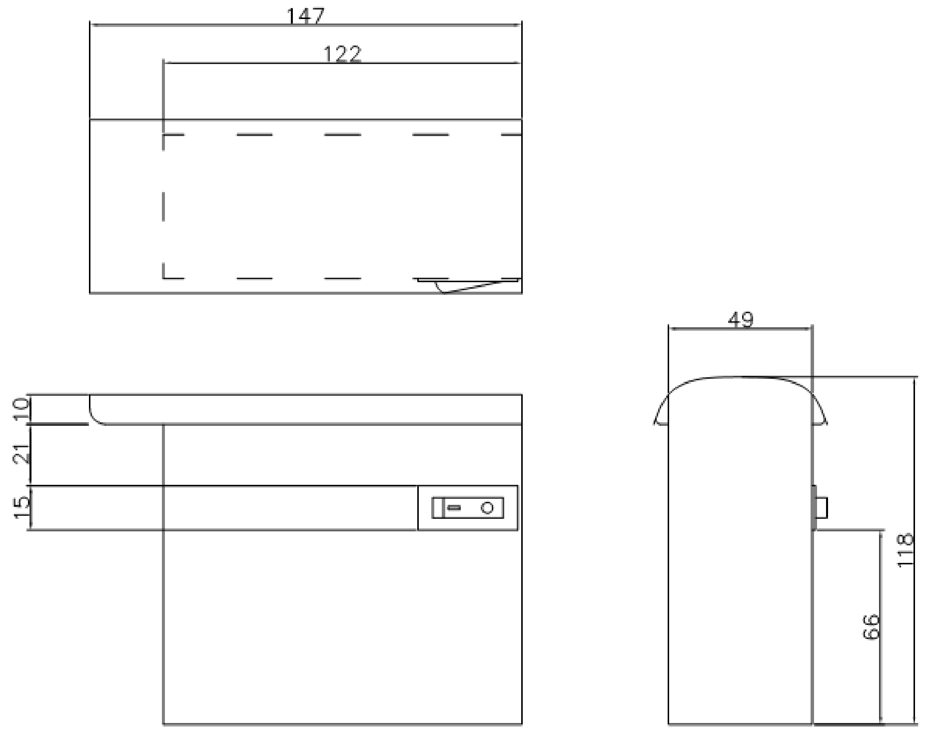
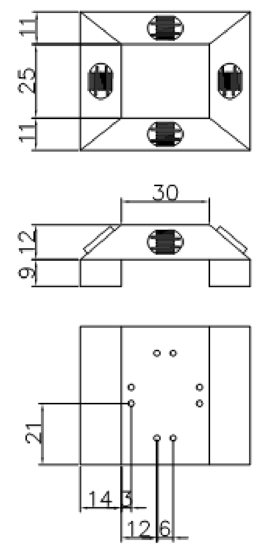


CIRCUITRY HOUSING



LDR SENSOR BLOCK

NOTES:
CIRCUITRY HOUSING CONSTRUCTED FROM A SHEET OF PVC PLASTIC. CUT THEN MOLDED USING A HEAT GUN.

LDR SENSOR BLOCK MILLED FROM A SOLID WOOD BLOCK. ALLOW HOLES FOR LDR PINS.
LDR BLOCK WEATHERPROOFED USING A SILICONE COATING.

DRAWING NAME LDR_BLOCK+CIRCUIT_HOUSING	
FILE NAME SCIENCE_FAIR_2014.DWG	
DRAWING NUMBER SF14-5	DRAWN BY J.SENIOR
	SCALE 1:2
DRAWN 02/05/2014	PRINTED 03/05/2014

2.1.3.2 Electronic

Below are the final electronic schematics:

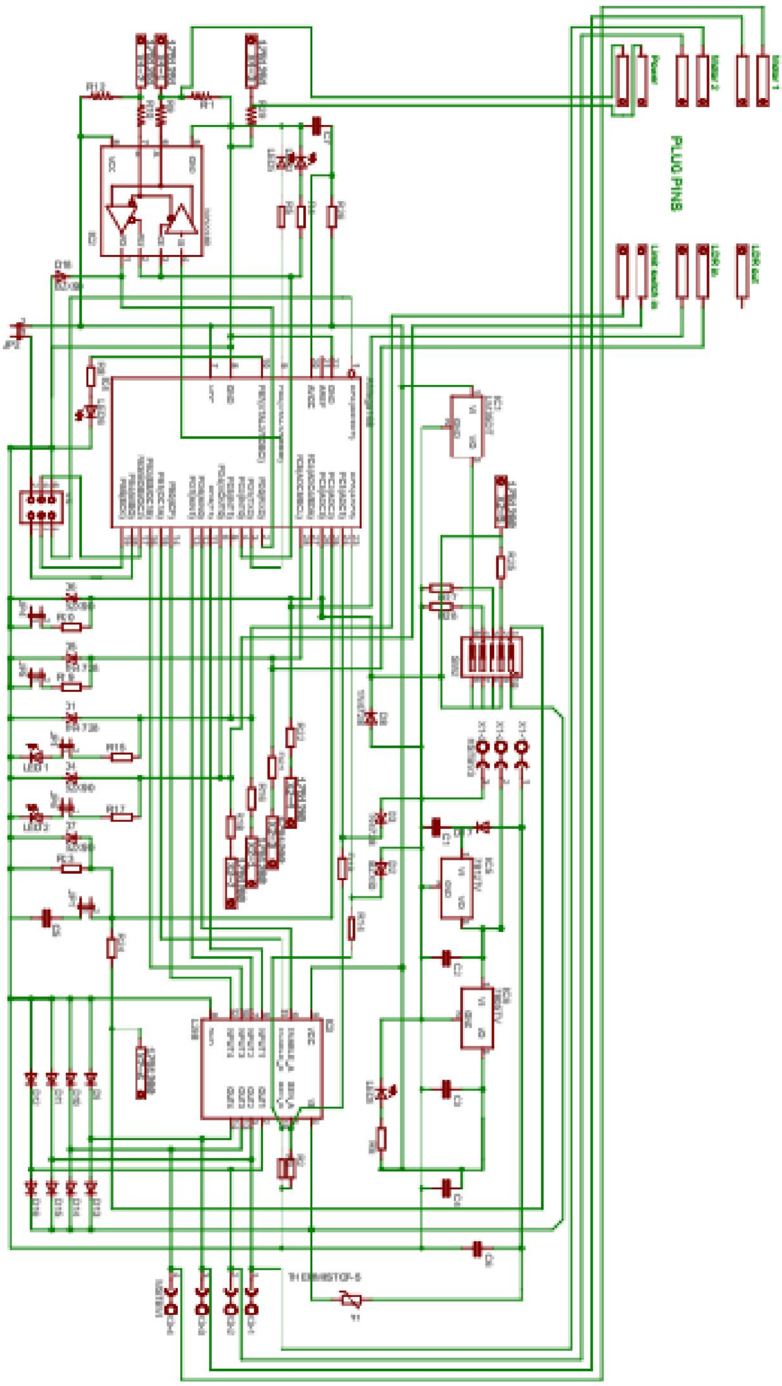


Figure 34: Prototype 1 Programmable Motor Driver circuit schematic

Note: Plug pins is a reference to the socket pins of the circuit board. The pins plugged into a socket which was mounted to the vertical pipe and was directly connected to all the electronics.

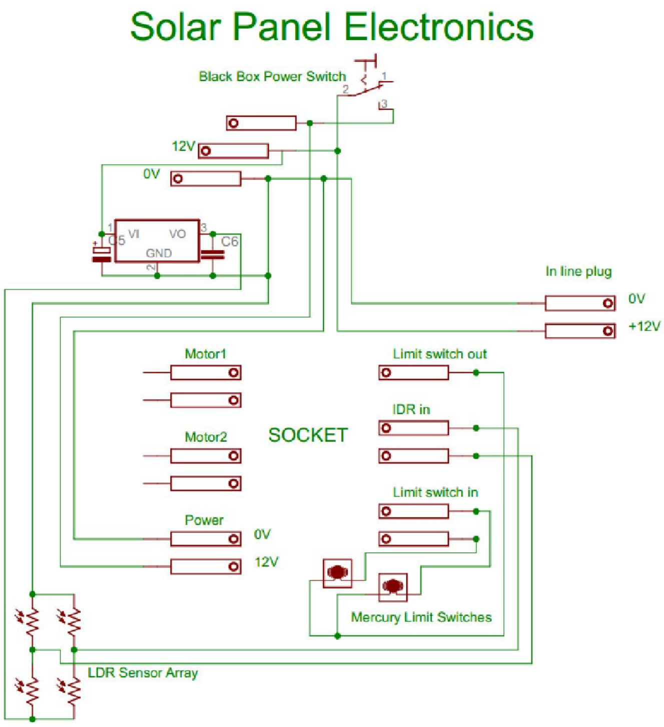


Figure 35: Prototype 1 On-board electronics schematic

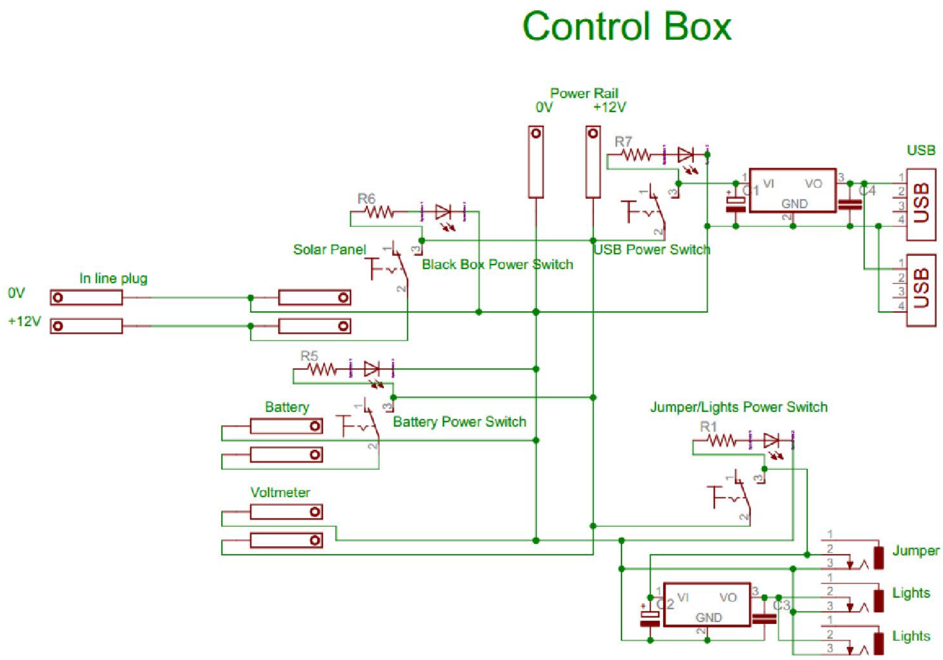


Figure 36: Prototype 1 Interface Box electronic

2.1.3.3 Programmed

This is the programmable hobbyist computer code for the active tracking system:

```
int mot1Enable = 10;                //defining "mot1Enable" as output pin 10
int mot1For = 5;                    //defining "mot1For" as output pin 5
int mot1Rev = 7;                    //defining "mot1Rev" as output pin 7

int mot2Enable = 9;                 //defining "mot2Enable" as output pin 10
int mot2For = 6;                    //defining "mot2For" as output pin 10
int mot2Rev = 8;                    //defining "mot2Rev" as output pin 10

int analog1 = A5;                   //defining "analog1" input as pin A5 (This is the LDR input for axis 1)
int analog2 = A4;                   //defining "analog2" input as pin A4 (This is the LDR input for axis 2)
int analogueValue1 = 0;             //defining a variable "analogueValue1" to use in the program (This will be the value of the LDR input for axis 1)
int analogueValue2 = 0;             //defining a variable "analogueValue2" to use in the program (This will be the value of the LDR input for axis 2)

int limit1 = 3;                     //defining limit1 as input pin 3
int limit2 = 4;                     //defining limit2 as input pin 4
int limit1State = 0;                //defining a variable to use in the program (This will be the current state of limit1)
int limit2State = 0;                //defining a variable to use in the program (This will be the current state of limit2)

int deadzone = 20;                  //defining "dead zone" as a variable proportional to the angle (not directly) either side of the normal that the
                                    solar panel does not have to adjust itself
int center1 = 255;                  //defining "center1" as a variable equal to the centre point of axis 1
int center2 = 285;                  //defining "center2" as a variable equal to the centre point of axis 2

int delay1 = 0;                     //defining "delay1" as counter variable used in order to prevent the motors from changing direction
                                    instantaneously (axis 1)
int delay2 = 0;                     //defining "delay2" as counter variable used in order to prevent the motors from changing direction
                                    instantaneously (axis 2)
int counterThreshold = 100          //defining "counterThreshold" as a variable equal to the threshold to which the counters need to count to in
                                    order to change direction


void setup() {                      //defining all the pins that need to be used as outputs as outputs
 pinMode(mot1Enable, OUTPUT);
 pinMode(mot1For, OUTPUT);
 pinMode(mot1Rev, OUTPUT);
 pinMode(mot2Enable, OUTPUT);
 pinMode(mot2For, OUTPUT);
 pinMode(mot2Rev, OUTPUT);
}

void loop()                         //beginning of loop
{
 limit1State = digitalRead(limit1);         //digitally read (HIGH or LOW) the variable: limit1 (input pin 3) and make itequal to the variable: limit1state
 limit2State = digitalRead(limit2);         //digitally read (HIGH or LOW) the variable: limit2 (input pin 4) and make it equal to the variable: limit2state
 analogueValue2 = analogRead(analog2);      //analogue read (any integer from 0 to 32768) the variable:analog2 and make it equal to the
varaible:analogueValue2
 analogueValue1 = analogRead(analog1);      //analogue read (any integer from 0 to 32768) the variable:analog1 and make itequal to the
varaible:analogueValue1

 if ((analogueValue1 > (center1 + deadzone)) && (limit1State == HIGH) )      //if all the conditions (analogueValue1 > (center1 + dead zone)) and (limit1State= HIGH)
are satisfied,                                                                the following will happen:
 {
  digitalWrite(mot1Rev, LOW;                //switch the pin: mot1Rev off
  digitalWrite(mot1For, HIGH;               //switch the pin: mot1For on
  if (delay1 < counterThreshold) delay1++;  //if the delay1 variable < counterThreshold add 1 the countervariable: delay1
  if (delay1 >= counterThreshold) digitalWrite(mot1Enable, HIGH);        //if the delay1 variable >= counterThreshold switch on the mot1Enable pin
 }

 else if ((analogueValue1 < (center1 - deadzone)) && (limit2State == HIGH) )   //if the previous conditions weren't satisfied and these conditions:
                                                                               (analogueValue1 < (center1 - dead zone) and (limit2State = HIGH) are satisfied, the
following will                                                                  happen:
 {
  digitalWrite(mot1For, LOW);`                                            //switch the pin: mot1For off
  digitalWrite(mot1Rev, HIGH);                                            //switch the pin: mot1Rev on
  if (delay1 < counterThreshold) delay1++;                                //if the delay1 variable < counterThreshold add 1 the counter variable: delay1
  if (delay1 >= counterThreshold) digitalWrite(mot1Enable, HIGH;          //if the delay1 variable >= counterThreshold switch on the mot1Enable pin
 }
```

```
else                                                        //if none of the above conditions were satisfied:
{
  digitalWrite(mot1Enable, LOW);                            //switch all motor pins off
  digitalWrite(mot1For, LOW);                               //switch all motor pins off
  digitalWrite(mot1Rev, LOW);                               //switch all motor pins off
  delay1 = 0;                                               //reset the counter to 0 (delay1)
}

if (analogueValue2 > (center2 + deadzone))                  //if the following conditions are satisfied: (analogueValue2 > (center2 +dead zone))
{
  digitalWrite(mot2Rev, LOW);                               //switch the pin: mot2Rev off
  digitalWrite(mot2For, HIGH);                              //switch the pin: mot2For on
  if (delay2 < counterThreshold) delay2++;                  //if the delay2 variable < counterThreshold add 1 the counter variable:delay2
  if (delay2 >= counterThreshold) digitalWrite(mot2Enable, HIGH);   //if the delay2 variable >= counterThreshold switch on the mot2Enable pin
}

else if (analogueValue2 < (center2 - deadzone))             //if the previous conditions weren't satisfied and these conditions:(analogueValue2 <
(center2 -                                                  dead zone) are satisfied, the followingwill happen:
{
  digitalWrite(mot2For, LOW);                               //switch the pin: mot2For off
  digitalWrite(mot2Rev, HIGH);                              //switch the pin: mot2Rev on
  if (delay2 < counterThreshold) delay2++;                  //if the delay2 variable < counterThreshold add 1 the counter variable:delay2
  if (delay2 >= counterThreshold) digitalWrite(mot2Enable, HIGH);   //if the delay2 variable >= counterThreshold switch on the mot2Enable pin
}

else                                                        //if none of the above conditions were satisfied:
{
  digitalWrite(mot2Enable, LOW);                            //switch all motor pins off
  digitalWrite(mot2For, LOW);                               //switch all motor pins off
  digitalWrite(mot2Rev, LOW);                               //switch all motor pins off
  delay2 = 0;                                               //reset the counter to 0 (delay
}
```

Most lines of the code are explained by a small inline annotation following a double forward slash. In the coding software, any text following a double forward slash, in a particular line has no coding effect, only annotative. This is the reason that this method is used to explain the individual lines of the code.

2.1.4 Prototype 1 Evaluation

2.1.4.1 Mechanical

The mechanical construction process went smoothly as the initial design proved to be almost identical to the end-product.

The design was well thought out and most issues were predicted.

The motors that were bought weren't geared down very far. This was a problem that had been expected. To resolve the issue, lubricant was used and unnecessary strain on rotating joints was alleviated.

Other than the motor gearing there were no major issues that needed addressing.

The final mechanical design is an extremely successful model. It functions as planned.

2.1.4.2 Electronic

The electronic design process was very successful.

There multiple major issues that needed resolving.

For each of the issues a solution was designed and built.

The final electronic design was very successful. It functioned better than what was originally planned.

2.1.4.3 Programmed

The programming was not planned at the start, but became a solution to an issue. It resolved the issue and improved the design's capabilities.

The programming went very smoothly and without any error. The logic was well thought out and as a result the program was fairly simple to write.

2.1.5 Prototype conclusions

The final product worked as planned. It was extremely capable of tracking the brightest light source visible to it. It also sufficiently charged the external power source and powered the outputs. It was not as portable as intended, but it was still able to be transported and set up easily.

Although it functioned well and as planned, it was far from perfect.
The design was not very stable and as a result wobbled in the wind or when moving.
The design is also asymmetrical due to the motor and sensor placement. This caused some minor imbalance of the product. The photovoltaic panel is fairly heavy, but is off center due to the design. The motor subsequently cannot provide the torque to slowly rotate the panel in its full rotation, it then flops over as it rotates. This is damaging to the components.

2.1.6 Prototype recommendations

- The next prototype should be made more sturdy. This can be achieved in multiple ways.
- Incorporation of three additional solar panels and an AC converter was considered, but this proved too cumbersome and expensive. A second generation model could be built that includes these features. This model would be designed as a more permanent fixture.
- To improve the portability of the current model a method of detaching parts could be implemented. A method must be found that allows ease of assembly and disassembly without reducing stability and sturdiness.

2.2 Prototype 2

2.2.1 Preliminary Design Procedure

2.2.1.1 Mechanical

One clear design emerged whilst conceiving prototype 2.

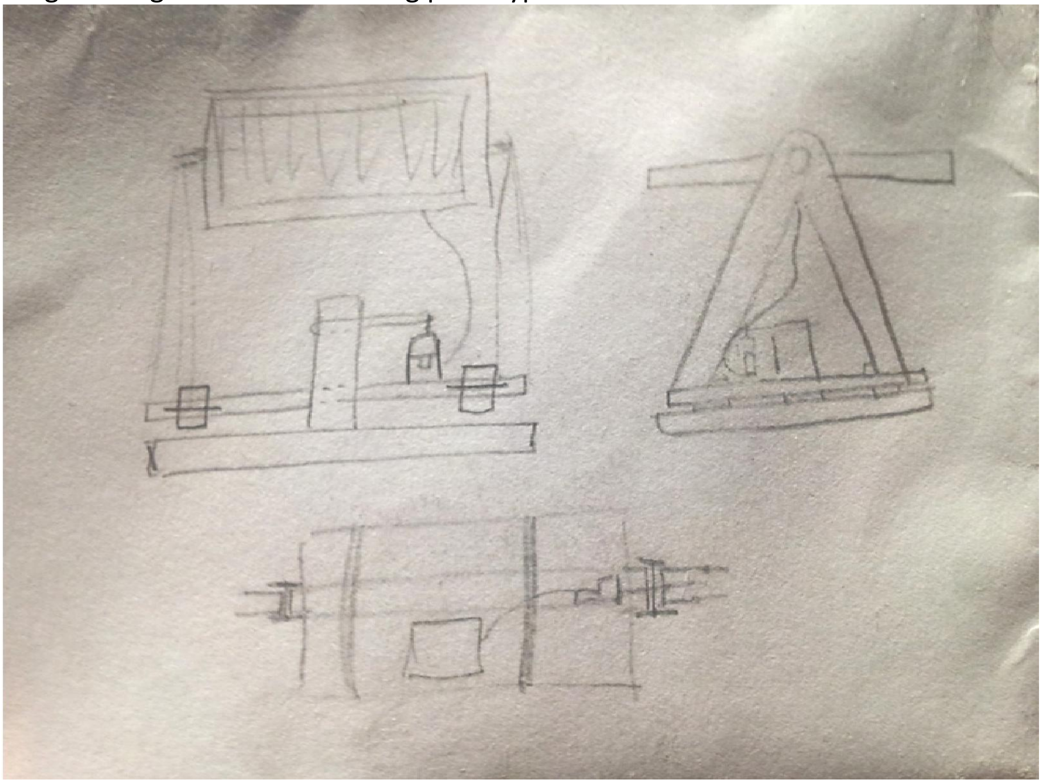


Figure 37: Prototype 2 Preliminary Design

To improve on prototype 1, prototype 2 would need to have been more stable. This could be done by utilizing a large, circular rotating base.
This prototype would likely be built out of wood.
The photovoltaic panels, of which there would now be two, would be mounted on two supports which will be attached to the base.
These supports will be detachable, allowing the prototype to be transported more easily.
A pulley system will be used to control the tilt of the panels. The pulley system allows for the prototype to be disassembled.
There would be a rotating connector between the layers of wood allowing for a an unrestricted 360° rotation around the base.

2.2.1.2 Electronic

The electronics designed for Prototype 1 will work well with Prototype 2. As such, almost no changes will be made to the design.

As the original circuits are already in use in prototype 1, new circuits will be built for prototype 2.

A rotating connection will be made to prevent the power cable from wrapping around the base of the prototype.

The same interface box will be used and the same battery.

Please refer to figures 24 - 26, on pages 28-30, for details on the electronics of prototype 1.

2.2.1.3 Programmed

The programming for Prototype 2 will be almost identical to Prototype 1. The motor settings will need to be adjusted to match the different motors and include the limit switch.

Please refer to chapter: 2.1.3.3 Programmed

2.2.2 Prototype 2 Development

2.2.2.1 Mechanical

The design for prototype 2 was developed further.

See below the developed sketch for prototype 2:

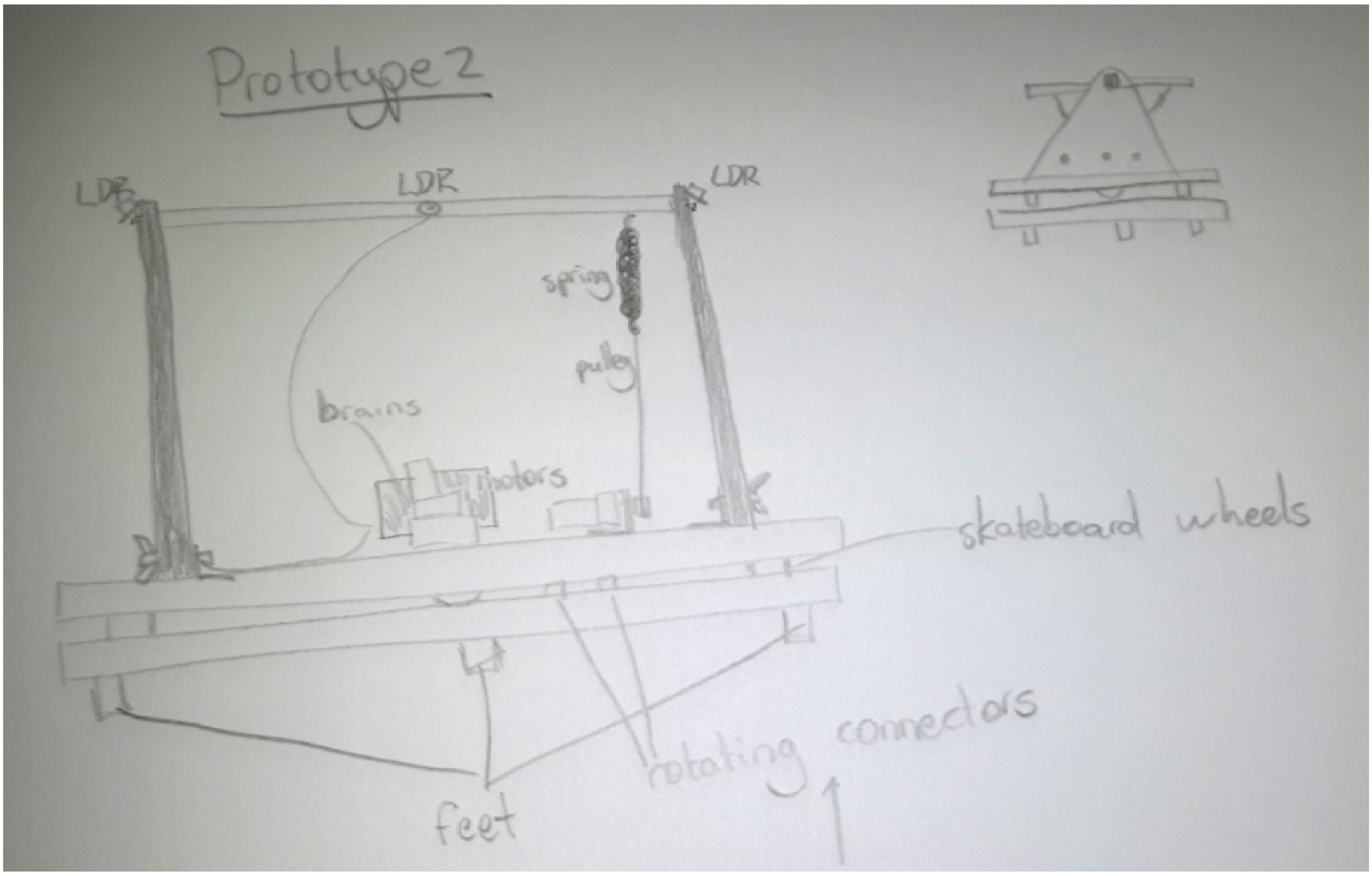


Figure 38: Prototype 2 Developed sketch

- In the refined design for prototype 2, the concept is the same. The photovoltaic panel angles towards the sun by rotating the tilt and yaw.
- The tilt is controlled by a motor with a pulley on the end. A spring-tensioned cable is attached to two points on the photovoltaic panel array and is wrapped around the pulley on the end of the motor.
- The yaw is controlled by a second motor that is attached with a bracket to the upper base. The axle protrudes through a hole in this base and is attached to the bottom, non-moving base.

- Two of the LDRs are mounted on the opposite edges of the photovoltaic panel array. The remaining two are fixed to the tops of the triangular support structures.
- The LDR brackets would be made out of aluminium profile that is bent at 45°.
- The mercury limit switches are mounted under the photovoltaic panel array. They are mounted at opposing angles of approximately 60°. This would need to be fine tuned to match the rotational range.
- The upper base would have four skateboard wheels mounted to the underside in order for the top base to rotate freely and easily on top of the bottom base.
- Four feet would be attached to the underside of the bottom base for support.
- The triangular support structures would be attached to the top base by a bracket. They would be attached to this bracket with wing nuts that can be tightened and loosed by hand. This allows for easy assembly and deconstruction.
- The pulley cable would need to be spring-tensioned. This will be required as the sum of the distances between the three points will not remain constant throughout the rotational range.

The following resources are required to construct Prototype 2. This list does not include the required electrical components:

- 2,5 m Angled aluminium 22 x 2 mm square
- 1 m Angled aluminium 38 x 2 mm square
- 1 m Flat bar aluminium 25 x 2 mm
- 2400 x 1200 x 18 mm Shutter ply wooden sheet
- 22x M4 x 10 mm Bolts
- 11x M4 x 30 mm Bolts
- 33x M4 Washers
- 41x M4 Nuts
- 500 mm Rubberized silicone pulley cable
- 4x Skateboard wheels with bearings
- 2x M8 x 4 mm Bearings
- 0,5 m M8 Threaded rod
- 14x M8 Washers
- 8x M8 Nuts
- 500 x 500 x 1 mm PVC sheet plastic
- 8x M3 x 10 mm Bolts
- PVC U - glue
- PVC Weld - glue
- Silicone sealant
- 2x drinking straws

The construction process of Prototype 2 can be found below. For measurements please refer to the technical drawings in chapter 2.2.3.1 Mechanical Computer-Aided Design (CAD) drawings

- Gather the required resources.
- Cut the wood into the specified shapes. There must be two triangular supports and two base discs.
- Drill and cut the required holes in the wood.
- Construct the mounts for the skateboard wheels and mount the wheels.
    - Cut the threaded rod into appropriate lengths.
    - Cut the aluminium strips to appropriate lengths.
    - Drill the screw holes through the aluminium.
    - Place the skateboard wheels on the threaded rod sections.
    - Use nuts and washers to hold the wheels in place.
    - Clamp the threaded rod (with the wheels attached) to the bottom of the upper wooden disc using the aluminium strips..
- Construct and mount the motor brackets to the wooden discs. Take care to line up the vertical motor with the L-shaped connection.
    - Cut and drill all aluminium as specified in the technical drawings. Take care while tapping the screw hole in the L-shaped connection.
- Mount the supports to the base using angled aluminium. Use wing nuts to attach the supports to the angled aluminium.
- Construct the photovoltaic panel support framework as detailed in the technical drawings.
- Remove all components from the wood. Sand, varnish, repeat. Apply a minimum of 3 coats.
- Allow varnish to dry fully before remounting all components.
- Construct the electronics shrouds using plastic sheeting. Cut using a hacksaw and bend using a heat gun.
- Attach all electronics using hot glue and/or silicon.
- Secure the shrouds over the electronics and waterproof using silicon.

Below are some photos that were taken during the construction process:

Figure 39: Prototype 2 Wood cut into shapes

Figure 40: Prototype 2 Attaching wheels to the underside of the top base

Figure 41: Prototype 2 Side triangular supports with brackets

Figure 42: Prototype 2 Triangles and skateboard wheels attached

Figure 43: Prototype 2 Attached motor brackets and motors

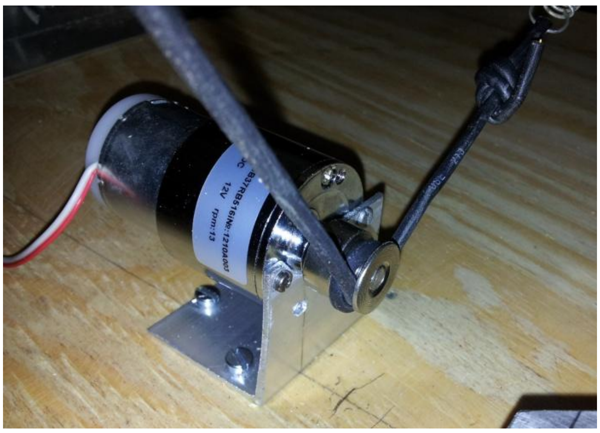


Figure 44: Prototype 2 Pulley and motor

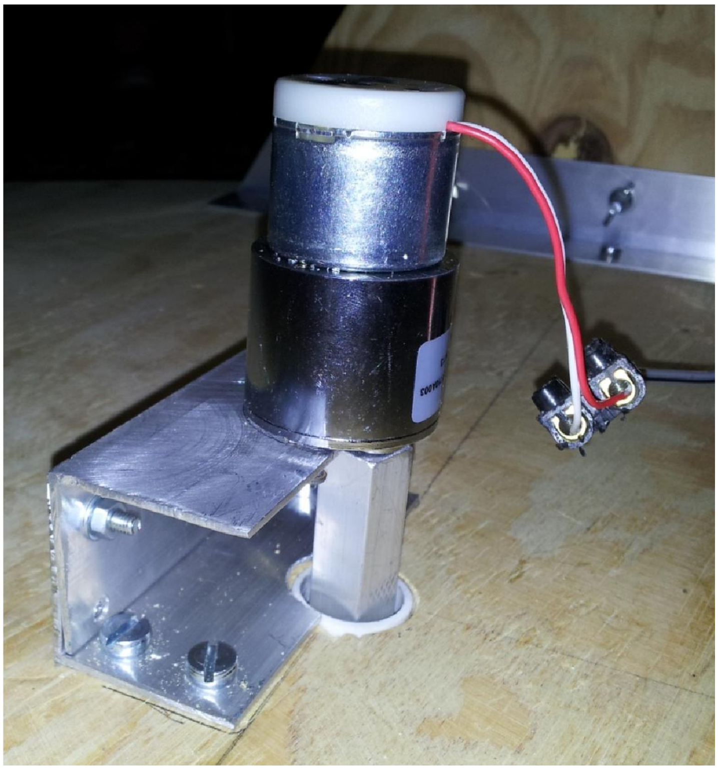


Figure 45: Prototype 2 Yaw motor and bracket

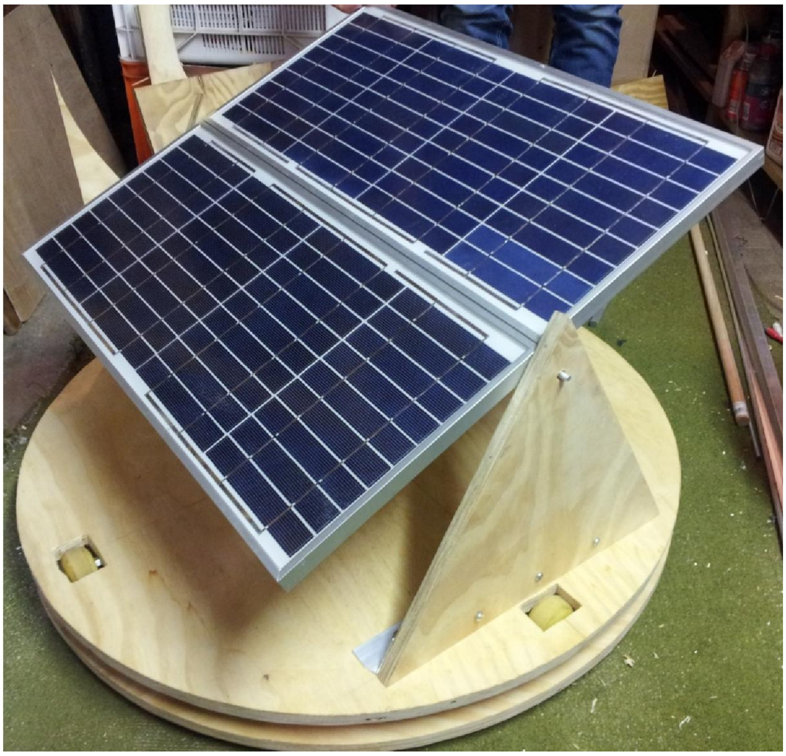


Figure 46: Prototype 2 Incomplete look

Figure 47: Prototype 2 Pulley and centre of gravity modification

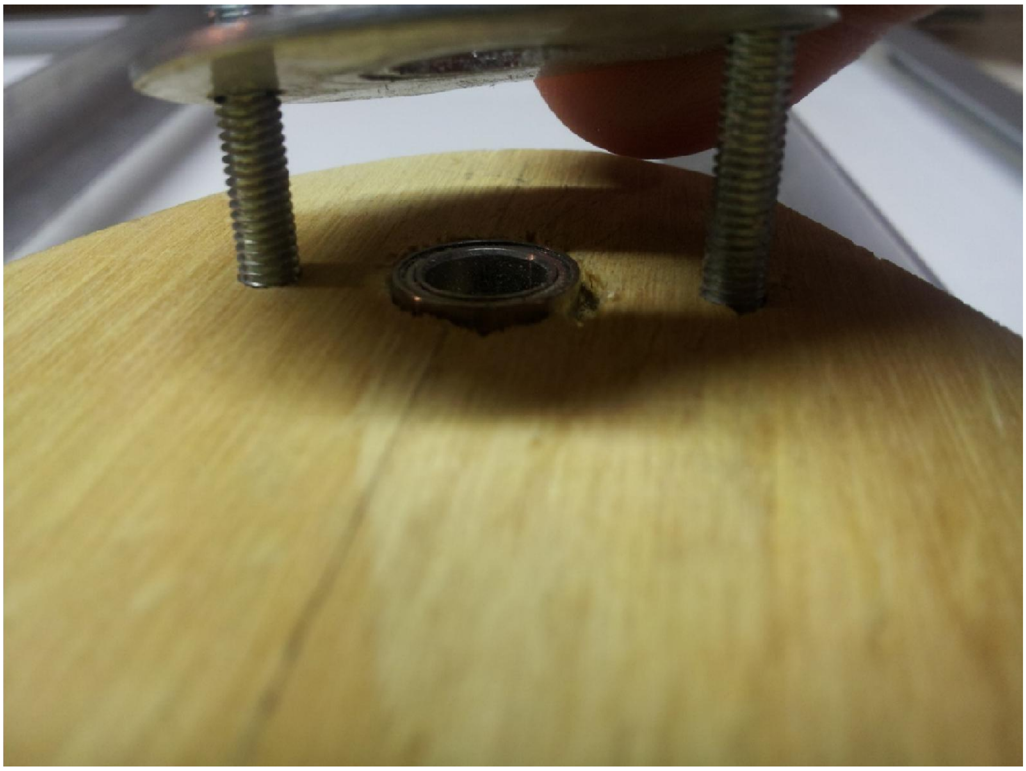


Figure 48: Prototype 2 Close-up on bearing

Figure 49: Prototype 2 Triangle LDR bracket

Figure 50: Prototype 2 Panel LDR bracket

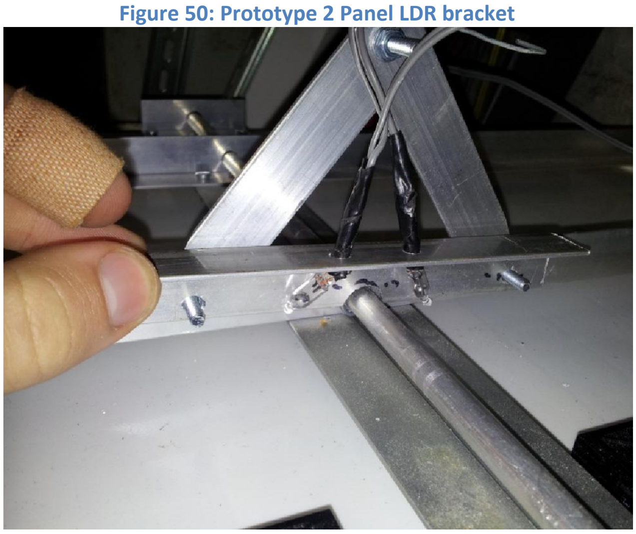


Figure 51: Prototype 2 Tilt limit switches

2.2.2.2 Electronic

The same electronic layout was used as was in prototype 1.

New circuits were built, but the designs remained the same.

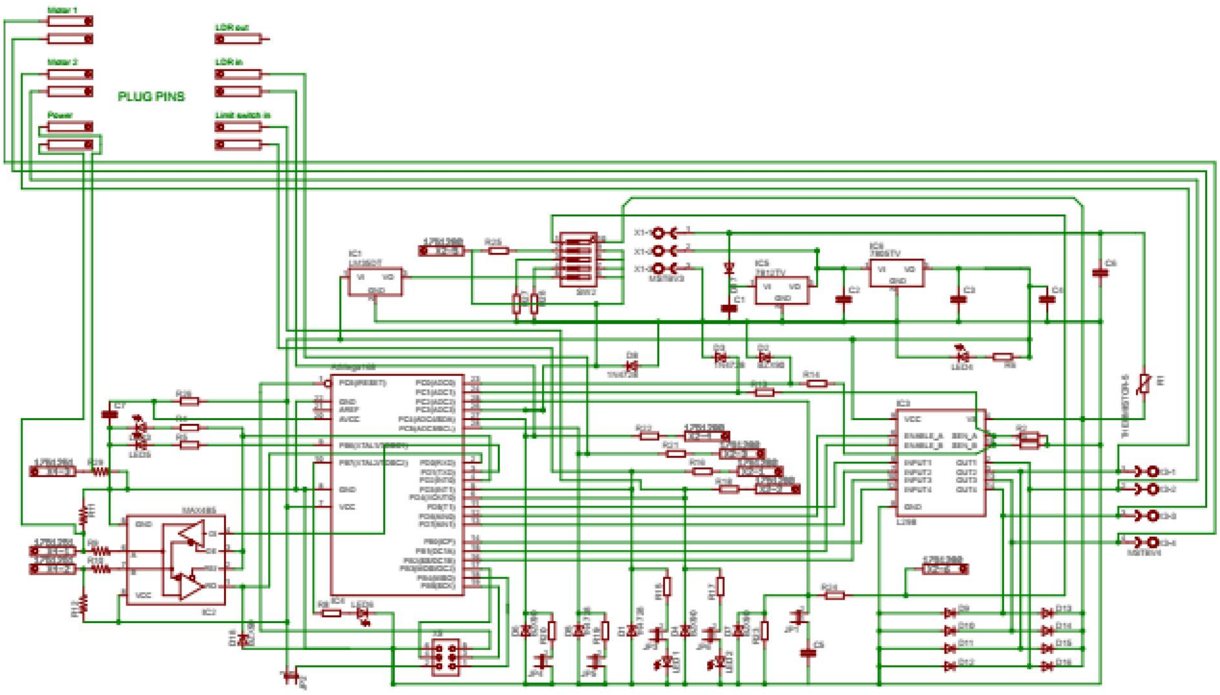


Figure 52: Prototype 2 Programmable Motor Driver circuit schematic

Plug pins is a reference to the socket pins of the circuit board. The pins plugged into a socket which was mounted to the vertical pipe and was directly connected to all the electronics.

In order to connect the electronics on the prototype to the electronics in the interface box, a long cable had to be made. Near the prototype a small in-line plug was put in the cable, for ease of packing and transporting.
A power switch was made to enable or disable the tracking capabilities.
A small 12V regulator was put in line before the LDRs. This was ensure a constant voltage input. This was because the photovoltaic panel had the ability to change the voltage. The sensors readings were skewed as a result of these voltage fluctuations. All the electronics on the prototype were routed to the single, multi-pin socket. This socket was where the motor driver board would plug in.

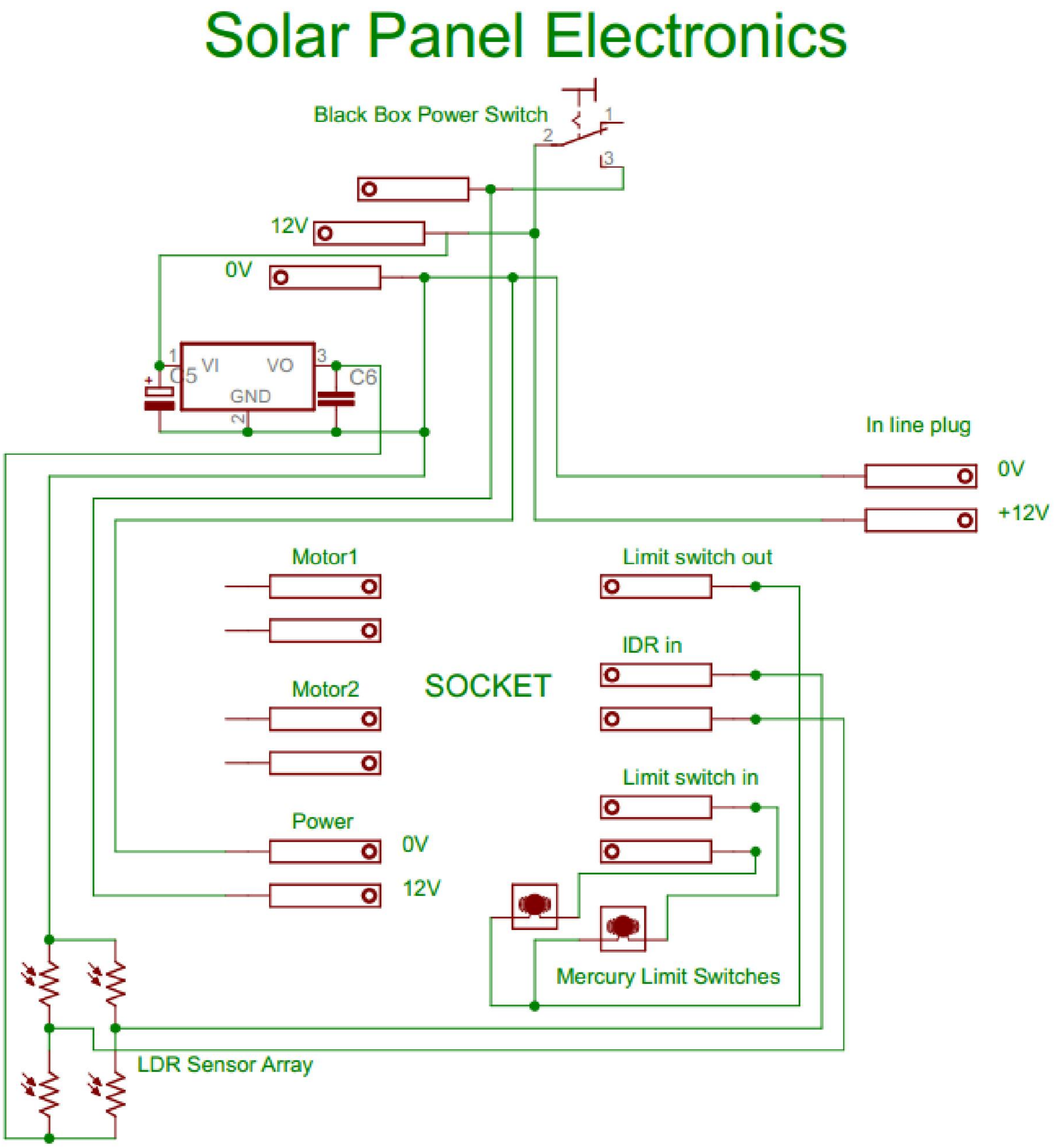


Figure 53: Prototype 2 On-board electronics

A 5 V regulator was put in line before the USB outputs. This was to ensure that the voltage outputs from the USB ports were always constant. USB ports are universally 5 V and this was a necessity for a charging port.

A 12 V regulator was put in line before the light outputs. This is order to maintain a constant 12 V. The lights that were used would get very hot if the voltage was any higher than 12 V.
A simple switch and LED with a resistor was put at each output to easily control outputs and monitor activity.

The jumper output is a direct connection to the battery and the photovoltaic panel. This would be used for charging other 12 V batteries or simply powering 12 V devices.

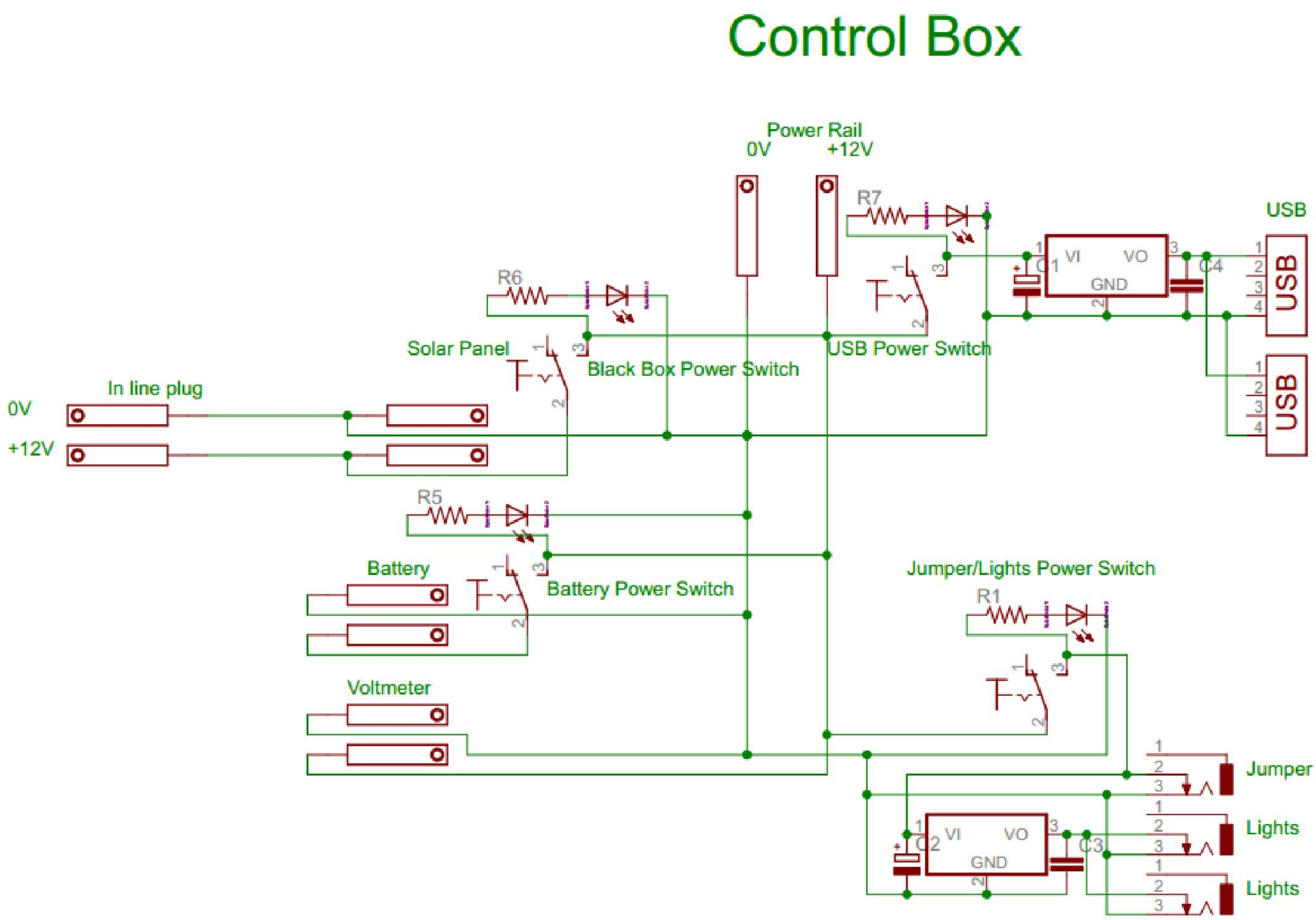


Figure 54: Prototype 2 Interface Box electronics

The previously described circuits were constructed. The parts list is shown below:

Electronics Part List:

- 2 x 12v 450mA 13 rpm motor
- 1 x 12v 40Ah car battery
- 4 x LDR 2kΩ 35v
- Electrical wire solid core copper
- 5x switch 200W
- Voltmeter 0-30v
- 2x USB port
- 4x DC power plug
- 4x DC power socket
- 1x 2,2kΩ resistor 1/4W
- 3x 1kΩ resistor 1/4W
- 4x 5mm Clear Blue LED
- 2x Mercury limit switch
- 2x 7812 12v 1A regulator
- 1x 7805 5v 1A regulator
- 3x 0,1µF 20v tantalum capacitor
- 3x 470µF 16v electrolytic capacitor
- 1x Driver87 board
- 1x AtMega168

2.2.2.3 Programmed

The programmable IC in the Driver87 board is compatible with an easily available hobbyist PC-on-a-board programmable via USB ports. This became the new centre of the system. With some programming the effects of the simple logic circuit were emulated. Being programmable made it much easier to make timing changes, add delays and add preventative measures.

The program had to follow a certain logical pattern.
See below a sketch illustrating the logic used to create the program:

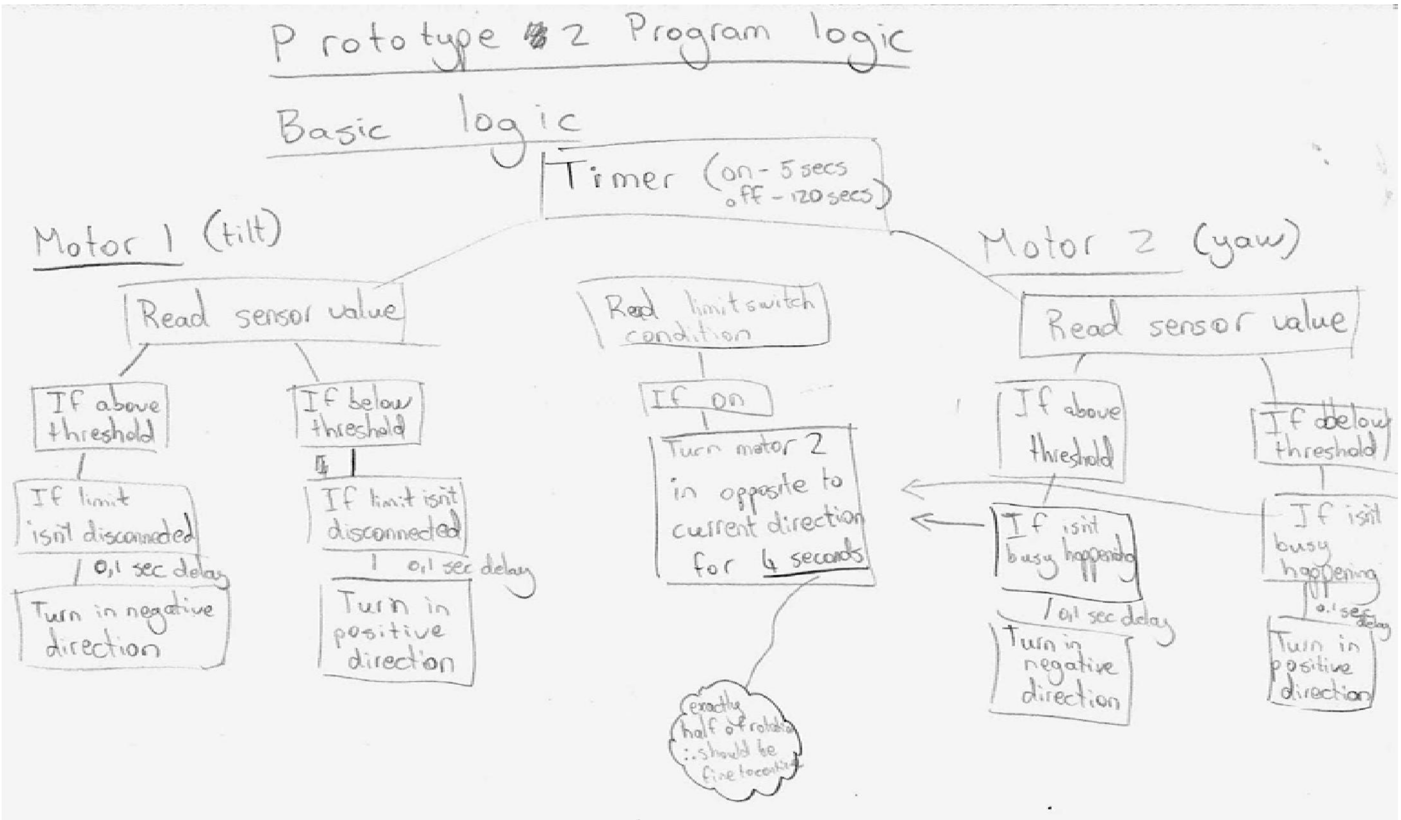


Figure 55: Prototype 2 Program logic sketch

2.2.3 Prototype 2 Final Design

2.2.3.1 Mechanical Computer-Aided Design (CAD) drawings

The mechanical design process went smoothly as the initial design proved to be almost identical to the end-product, besides some minor issues that have been resolved.

The final mechanical design is an extremely successful model. It functions as intended. After the initial build there were a few minor issues as the original design included a 360° rotating power connector. The purpose of this would be to prevent the cables tangling. It was found after extensive testing that this was not a viable plan. It was decided that this should be removed and, in its place, a algorithm has been programmed into the motor driver only allowing for a 360° range of motion. This solves the issue of tangling cables and is also very simple.

See below the following photo of the complete prototype:

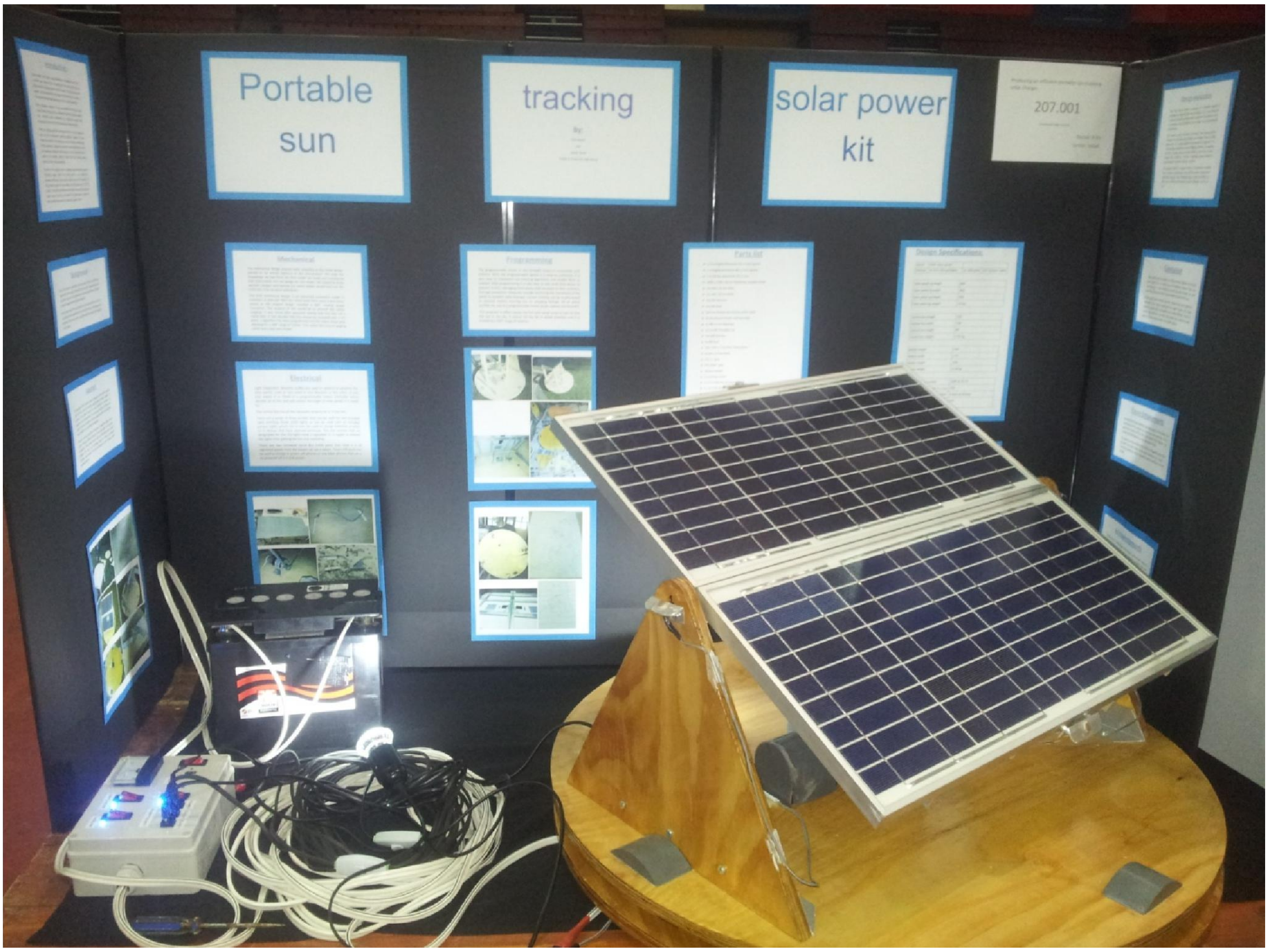


Figure 56: Prototype 2 Complete Photo

Design features:

Inputs:	25 W solar panel		
Outputs:	2x 12 V LED spotlights	2x USB ports	12 V jumper cable

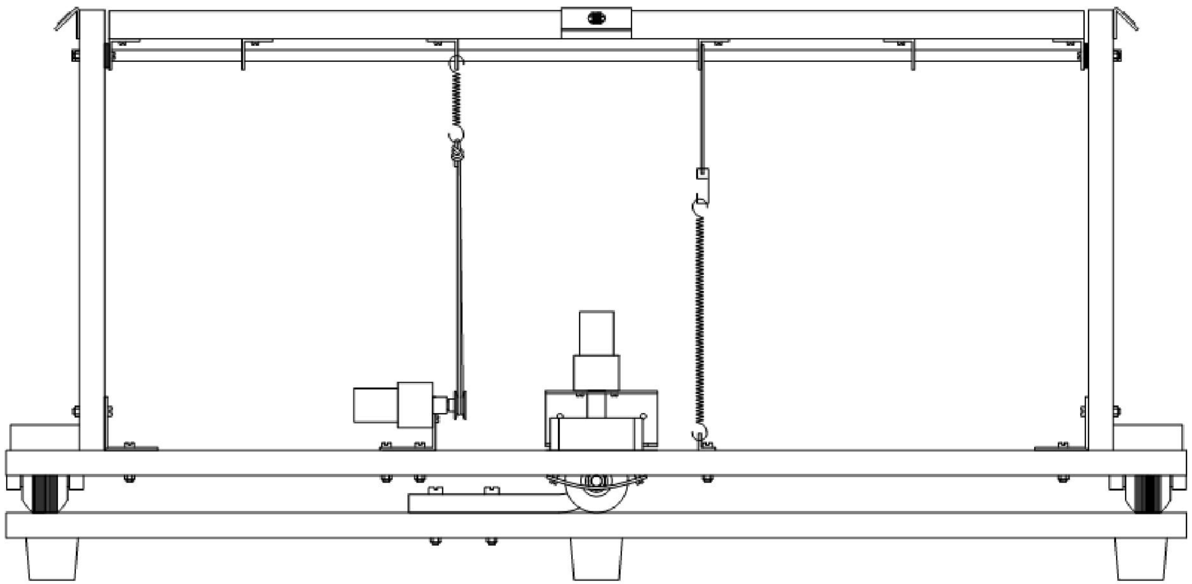
Total length	880 mm
Total width	880 mm
Total height max	640 mm
Total weight	20 kg

Control box length	194 mm
Control box width	146 mm
Control box height	90 mm
Control box weight	0.55 kg

Battery length	240 mm
Battery width	170 mm
Battery height	200 mm
Battery weight	12.8 kg

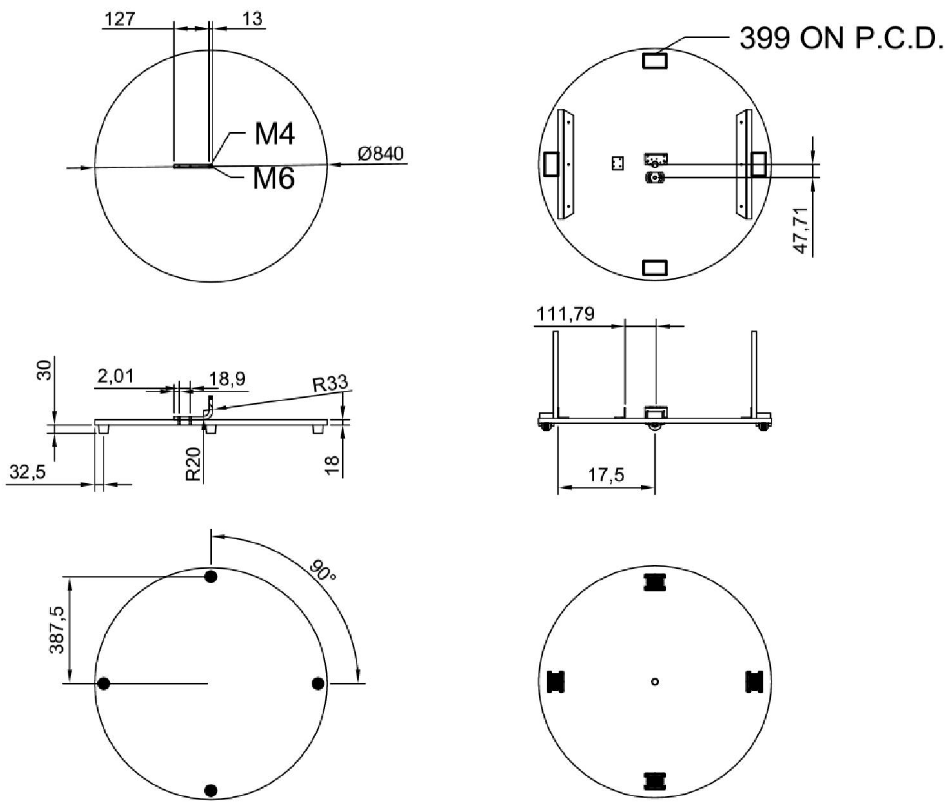
Maximum power output	50 W at 22.7 V
Minimum battery charging time- direct sunlight	15h
Estimated average charging time	4 days at 5 h/day
Absolute peak discharge time- battery only	12 h

For details and measurements regarding construction, please see the technical drawings on the following pages:



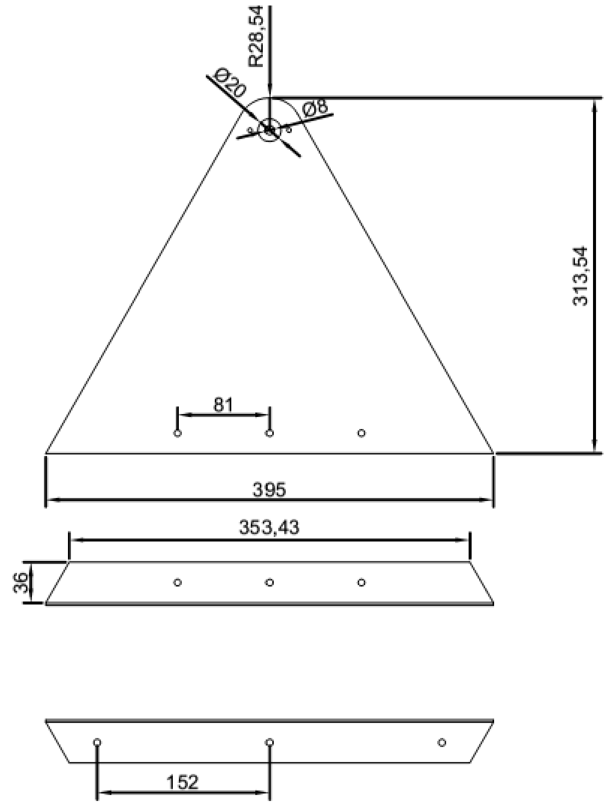
NOTES:
FOR PRECISE MEASUREMENTS SEE OTHER DRAWINGS

DRAWING NAME ASSEMBLED VIEW	
FILE NAME SCIENCE FAIR 2014 MkII.dwg	
DRAWING NUMBER SF14-1	DRAWN BY J.SENIOR
	SCALE 1:4
DRAWN 11/08/2014	PRINTED 18/08/2014



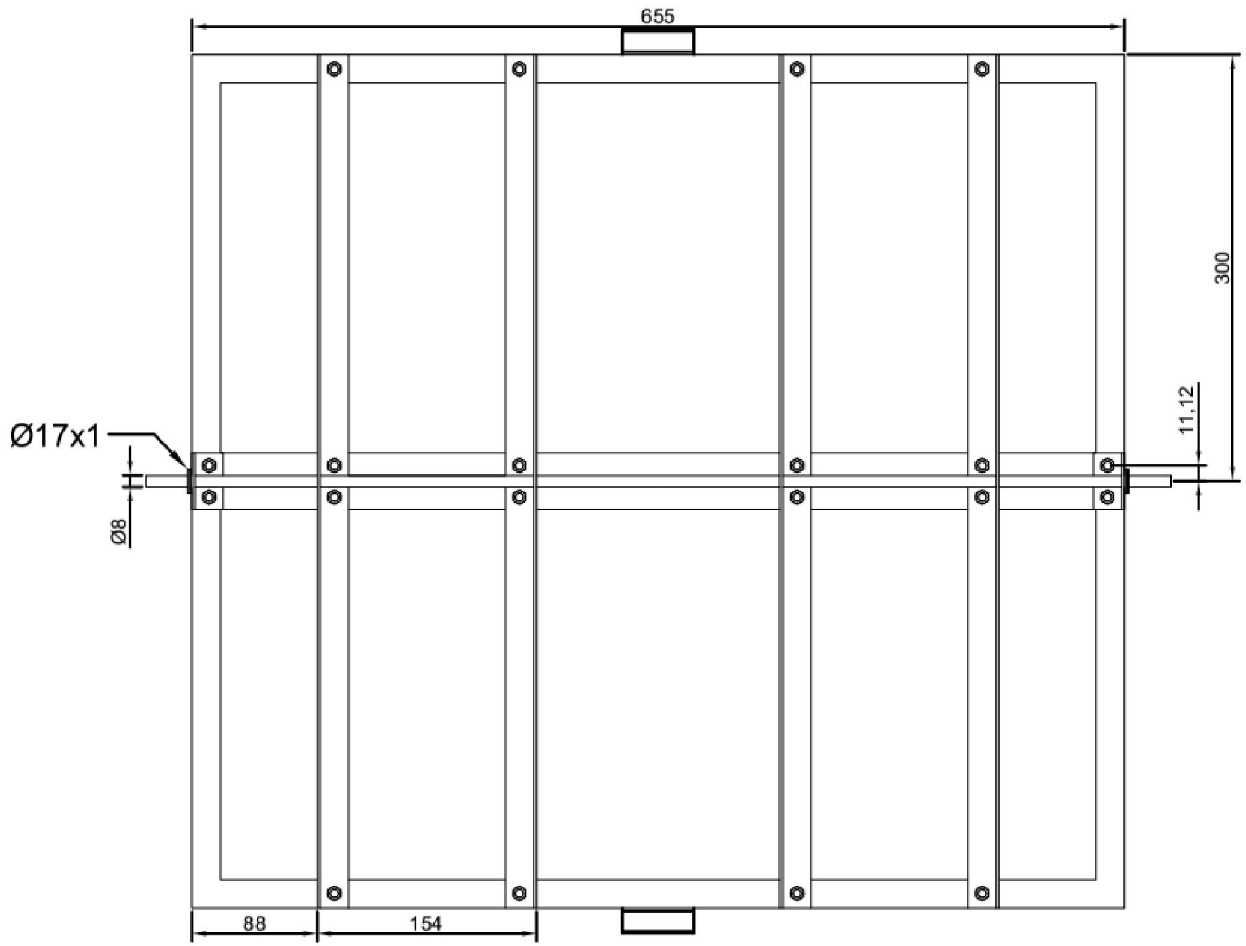
NOTES:
WOOD THICKNESS MAY NOT BE CONSTANT DUE TO SANDING AND VARNISHING

DRAWING NAME	PARTIAL ASSEMBLED TURNTABLE		
FILE NAME	SCIENCE FAIR 2014 MkII.dwg		
DRAWING NUMBER	SF14-2	DRAWN BY	J.SENIOR
		SCALE	1:20
DRAWN	11/08/2014	PRINTED	18/08/2014



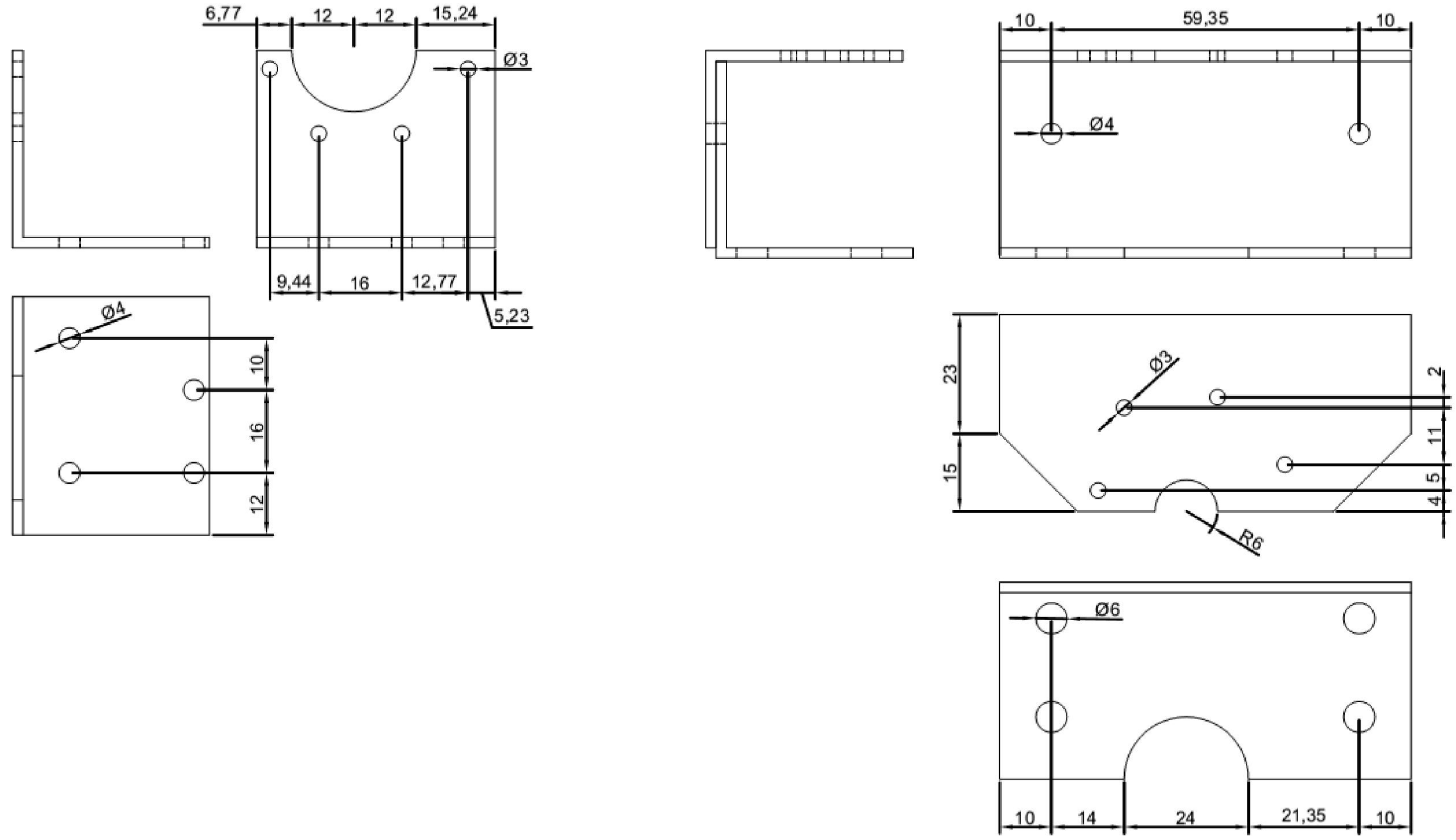
NOTES:
HOLES ARE M6 UNLESS OTHERWISE SPECIFIED

DRAWING NAME SUPPORT TRIANGLES	
FILE NAME SCIENCE FAIR 2014 MkII.dwg	
DRAWING NUMBER SF14-3	DRAWN BY J.SENIOR
	SCALE 1:5
DRAWN 11/08/2014	PRINTED 18/08/2014



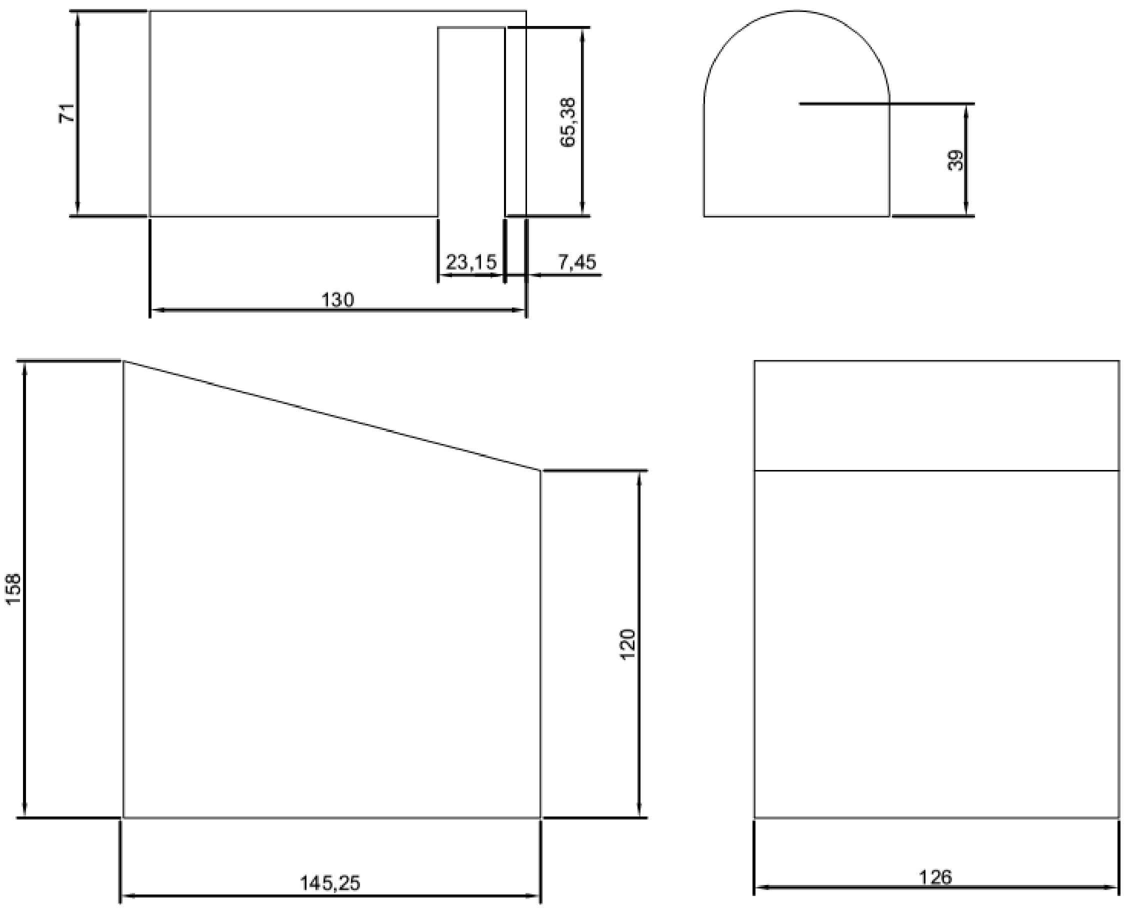
NOTES:
ALL HOLES ARE M4 UNLESS OTHERWISE SPECIFIED
ALL ANGLED ALUMINIUM IS 22X2

DRAWING NAME SOLAR PANEL FRAMEWORK	
FILE NAME SCIENCE FAIR 2014 MkII.dwg	
DRAWING NUMBER SF14-4	DRAWN BY J.SENIOR
	SCALE 1:4
DRAWN 11/08/2014	PRINTED 18/08/2014



DRAWING NAME MOTOR BRACKETS	
FILE NAME SCIENCE FAIR 2014 MkII.dwg	
DRAWING NUMBER SF14-5	DRAWN BY J.SENIOR
	SCALE 1:1
DRAWN 11/08/2014	PRINTED 18/08/2014

NOTES:
ANGLED ALUMINIUM IS 38X2 UNLESS OTHERWISE SPECIFIED



NOTES:
HOUSINGS ARE MADE FROM PVC PLASTIC

DRAWING NAME ELECTRONIC SHROUDS	
FILE NAME SCIENCE FAIR 2014 MkII.dwg	
DRAWING NUMBER SF14-6	DRAWN BY J.SENIOR
	SCALE 1:1
DRAWN 11/08/2014	PRINTED 18/08/2014

2.2.3.2 Electronic

The “SOCKET” annotation is a reference to the connecting block into where the Driver87 board connects.

The in-line plugs are representative of the physical construction of these circuits. There is a lead connecting the control box to the solar panel with an in line plug.

The following schematic is the schematic of the Driver87 Board that controls the system:

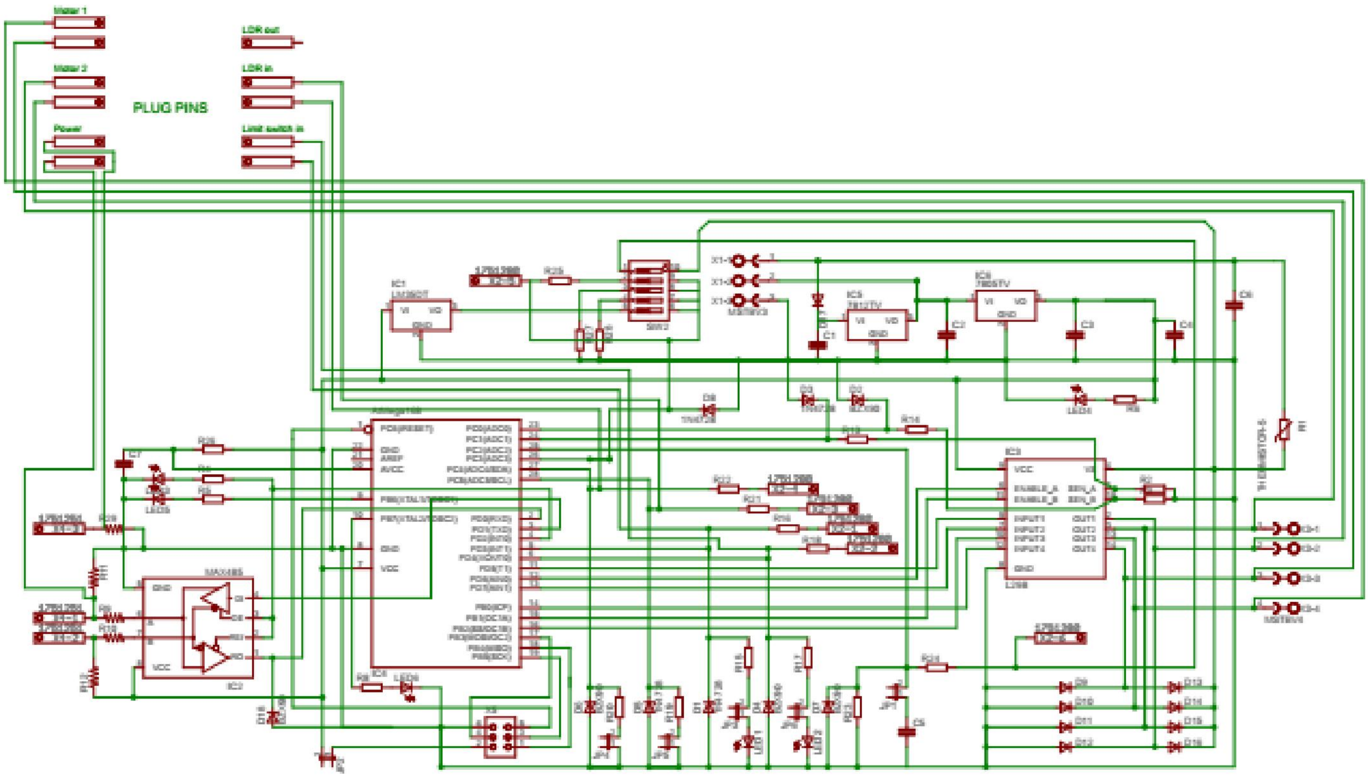


Figure 57: Prototype 2 Programmable Motor Driver circuit schematic

Note:
The “PLUG PINS” annotation is a reference to the pins of the plug with which the Driver87 board connects to the rest of the circuit.

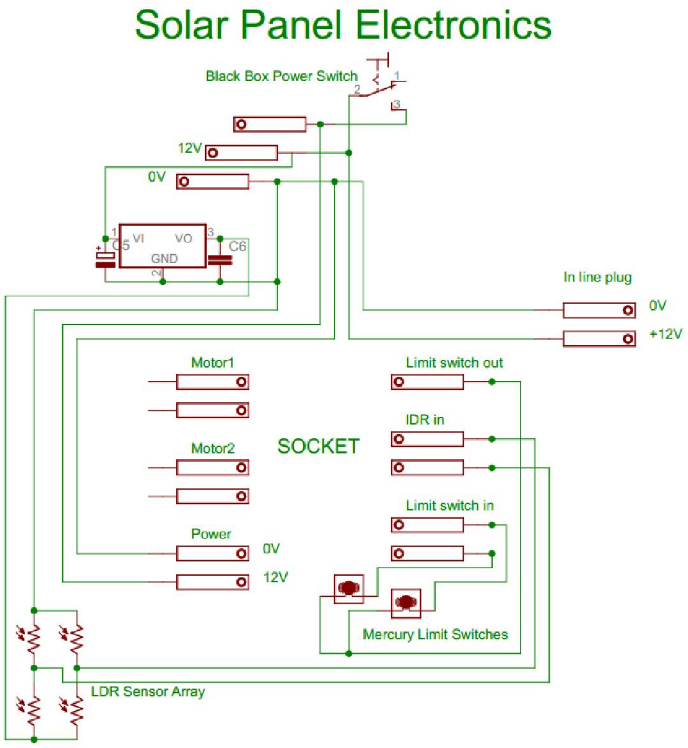


Figure 58: Prototype 2 On-board electronics schematic

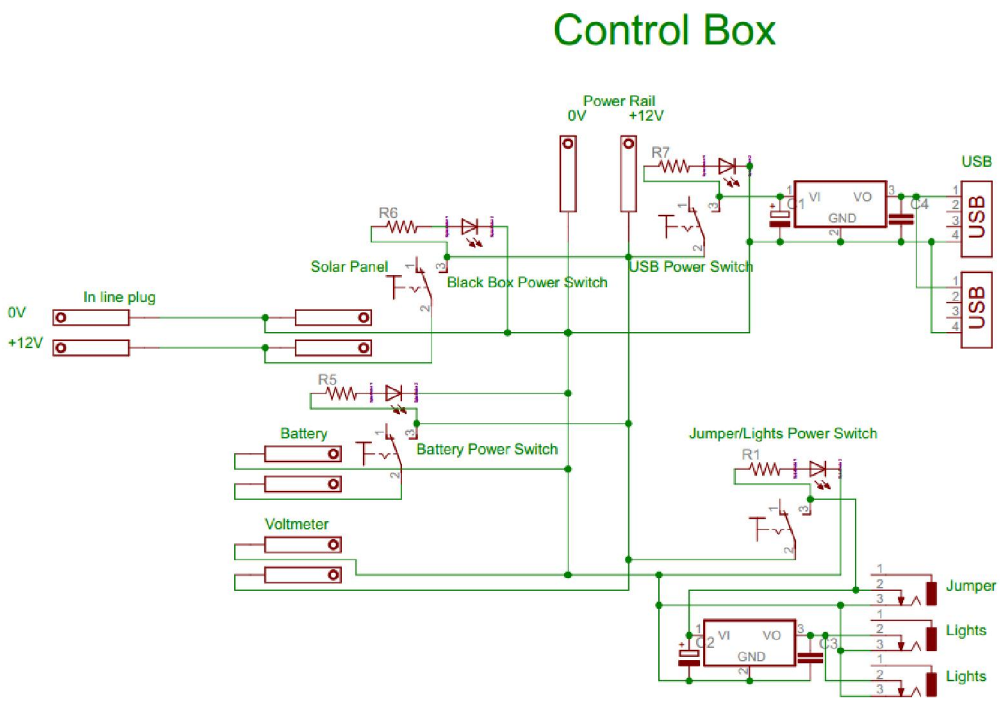


Figure 59: Prototype 2 Interface Box electronics schematic

2.2.3.3 Programmed

The programmable IC in the Driver87 board is compatible with an easily available hobbyist PC-on-a-board programmable via USB ports. Programming allows for greater management of the sun tracking algorithm, as well as adding small delays to prevent damage to the motors, their brackets or their receivers. Damage prevention measures include restricting the movement of the panel to prevent cable damage. Current limiting can be implemented to prevent motors burning out or stripping fittings. All of above justifies the use of the Driver87.
This program causes the solar panel array to turn to face the sun in the sky. It cannot tilt too far in either direction and it is limited to a 360° range of rotation.
This is the code for the active tracking system:

```
int mot1Enable = 10;
int mot1For = 5;
int mot1Rev = 7;

int mot2Enable = 9;
int mot2For = 6;
int mot2Rev = 8;
boolean mot2ForBool = false;
boolean mot2RevBool = false;

int analog1 = A5;
int analog2 = A4;
int analogueValue1 = 0;
int analogueValue2 = 0;

int limit1 = 3;
int limit2 = 4;
int limit1State = 0;
int limit2State = 0;

introtateSwitch = A3;
introtateSwitchState = 0;
introtateCounter = 0;
booleanrotCountOneShot = false;
introtateMax = 2;
introtateMin = -2;
booleanrotSwBool = false;
boolean untangling = false;
booleanuntangleReverse = false;
booleanuntangleForward = false;

int deadzone1 = 5;
int deadzone2 = 60;
int center1 = 255;
int center2 = 285;

int delay1 = 0;
int delay2 = 0;


void setup()
 {
		pinMode(mot1Enable, OUTPUT);
		pinMode(mot1For, OUTPUT);
		pinMode(mot1Rev, OUTPUT);
		pinMode(mot2Enable, OUTPUT);
		pinMode(mot2For, OUTPUT);
		pinMode(mot2Rev, OUTPUT);
}

void loop()
{
		limit1State = digitalRead(limit1);
```

```
	limit2State = digitalRead(limit2);
	analogueValue2 = analogRead(analog2);
	analogueValue1 = analogRead(analog1);
	rotateSwitchState = analogRead(rotateSwitch);



	if ((analogueValue1 > (center1 + deadzone1)) && (limit1State == HIGH) && (untangling == false))
	{
		digitalWrite(mot1Rev, LOW);
		digitalWrite(mot1For, HIGH);
		if (delay1 < 100) delay1++;
		if (delay1 >= 100) digitalWrite(mot1Enable, HIGH);
	}

	else if ((analogueValue1 < (center1 - deadzone1)) && (limit2State == HIGH)  && untangling == false)
	{
		digitalWrite(mot1For, LOW);
		digitalWrite(mot1Rev, HIGH);
		if (delay1 < 100) delay1++;
		if (delay1 >= 100) digitalWrite(mot1Enable, HIGH);
	}


	else
	{
		digitalWrite(mot1Enable, LOW);
		digitalWrite(mot1For, LOW);
		digitalWrite(mot1Rev, LOW);
		delay1 = 0;
	}

	if (analogueValue2 > (center2 + deadzone2) && untangling == false)
	{
		mot2RevBool = false;
		mot2ForBool = true;
		digitalWrite(mot2Rev, LOW);
		digitalWrite(mot2For, HIGH);
		if (delay2 < 300) delay2++;
		if (delay2 >= 300) digitalWrite(mot2Enable, HIGH);
	}

	else if (analogueValue2 < (center2 - deadzone2) && untangling == false)
	{
		mot2ForBool = false;
		mot2RevBool = true;
		digitalWrite(mot2For, LOW);
		digitalWrite(mot2Rev, HIGH);
		if (delay2 < 300) delay2++;
		if (delay2 >= 300) digitalWrite(mot2Enable, HIGH);
	}

	else
	{
		mot2RevBool = false;
		mot2ForBool = false;
		digitalWrite(mot2Enable, LOW);
		digitalWrite(mot2For, LOW);
		digitalWrite(mot2Rev, LOW);
		delay2 = 0;
	}


	delay(1);
}
```

2.2.4 Prototype Evaluation

2.2.4.1 Mechanical

The results of the mechanical functionality of the prototype were mixed. It was extremely stable and the dual photoelectric panel design allowed for a large energy intake. It was also accurate in its tracking and reasonably weatherproof.
It was, unfortunately, too big to be called truly portable. Although it did not take up much vertical space due to the removable supports, the base was too large to be practical.

The mechanical design process went smoothly as the initial design proved to be almost identical to the end-product, other than some minors issue that have been resolved.
The final mechanical design is an extremely successful model. After the initial build there were a few minor issues as the original design included a 360° rotating power connector. The purpose of this would be to prevent the cables tangling. It was found after extensive testing that this was not a viable plan. It was decided that this should be removed and, in its place, a limit switch was built and programmed into the motor driver only allowing for a 360° range of motion. This solves the issue of tangling cables and is also very simple.

2.2.4.2 Electronic

The electronics functioned with almost no major problems. One issue of note was the lack of a fuse. Due to the batteries' high amperage this should have been part of the circuit.

2.2.4.3 Programmed

The programming, after a few edits, worked smoothly. The only issue occurred when light levels were too low for the program to comprehend. This caused the prototype to aimlessly spin.

2.2.5 Prototype testing

The prototype was tested in comparison to a stationary panel. The tests involved minimal measurements, but were mathematically predicted, extrapolated and interpolated. The results were not necessarily accurate or precise, but did however give a rough estimation of comparative efficiencies. The testing involved measuring the power at different times of the day with the photovoltaic panel facing the sun perpendicularly. During midday the power was measured at a range of different angles.

The two sets of data were then combined to predict the energy harnessed between prototype 2 and a stationary panel.

To test the power output, a resistor was put in series to the panel. A multi-meter was used to measure the potential difference across the resistor.
The power was calculated in accordance with the formula below.

$$\text{Power (watts)} = \frac{\text{volts}^2}{\text{resistance (ohms)}}$$

To find the optimum resistor, it was practically tested during midday with an adjustable resistor. The resistor was adjusted so that the potential difference measure was 18 V. Then to 15 V and finally to 10 V. At each of these points the photovoltaic panel was disconnected and the resistance was measured using the multi-meter. A parabola was created. Power being on the vertical axis and resistance on the horizontal.

The apex of the parabola was found to be at 13.5 Ω. It was decided that this would be the resistance used throughout the remainder of testing.

This method of testing power does not necessarily give the maximum power at a given time. Making use of maximum power point tracking techniques was considered. Prototype 2 testing occurred before the construction of prototype 3. It was decided that prototype 3 would deserve more precise testing and the basic testing techniques mentioned above would be sufficient for testing prototype 2 or at least having a prediction for how prototype 3 should perform.

Voltages were predicted at 15 minute intervals throughout the day. The results were then graphed.
The base measurements were measured during early spring. In theory, the total energy harnessed should improve during summer periods. The stationary panel was calculated at the optimum angle at the time of testing.

Calculations:

To calculate the power each time interval the following formula was used:

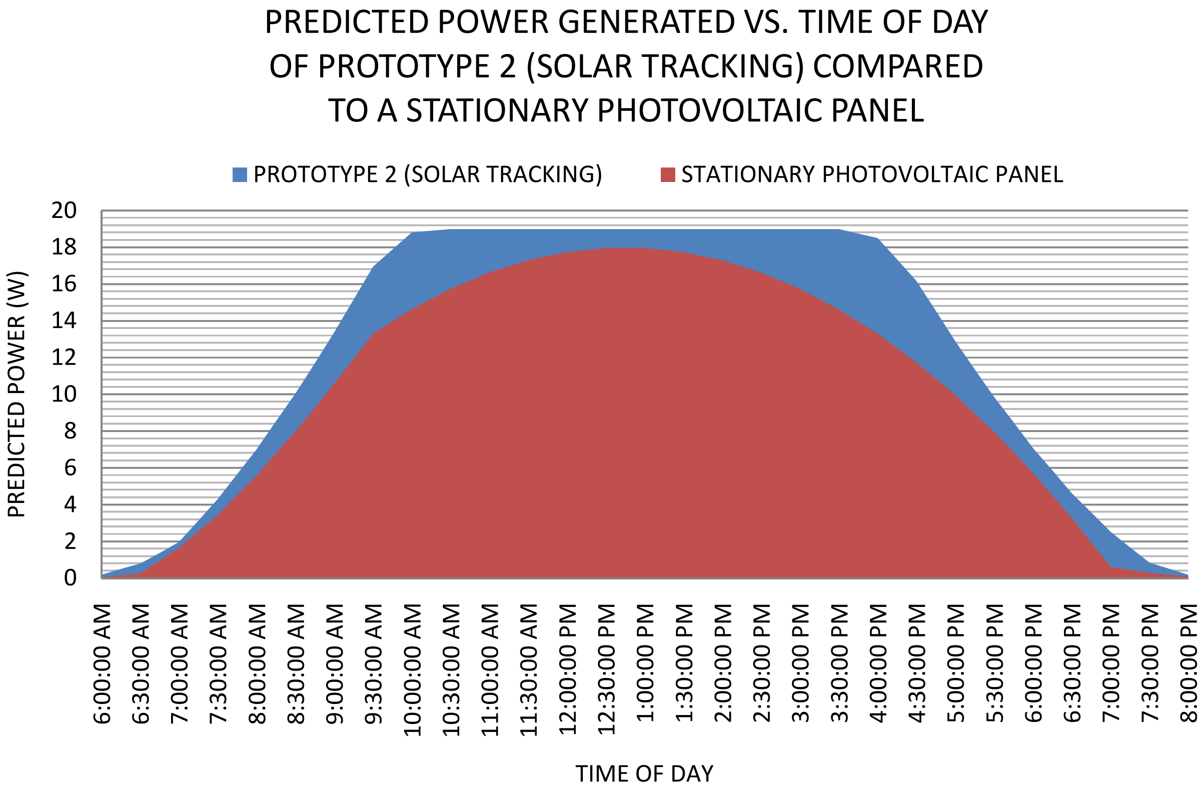
$$\text{Power (watts)} = \frac{\text{volts}^2}{\text{resistance (ohms)}}$$

To calculate the area underneath the graphs (total energy) the following method was used:

- Each individual quarter hour segment was calculated individually and then summed at the end.
- The formula to calculate the area of each segment is the following:
  - The first two power readings are added together and divided by two.
  - That value is then multiplied by 0,25 (representing a quarter of an hour, considering the area would be in Wh)
- The sum of the area equals the total accumulative energy.
- From the two accumulative energy values, a difference could be calculated.

2.2.6 Prototype results

The sum of all the individual areas for the tracking prototype is 177.5068 Wh and is 136.0865 Wh for the stationary panels. 177.51 divided by 136,09 is 1.3044. Therefore tracking the sun tracking prototype benefits 30.44% more energy.



2.2.7 Prototype testing results discussion

As is evident, sun tracking has clear power production benefits. This power production is approximately 30.44% higher than that of the stationary panel. This takes into account the power used by the tracking circuit. This tracking circuit uses very little power. The use is below 0.1 A at any point in time if it is not moving. When moving it can use up to 0.7 A. The panel can only move at a maximum of one second every minute, this can be calculated to 12.5 minutes per day and the maximum that the tracking circuit can draw is 7.6 W. This is equivalent to 1.45 Watt hours (Wh). Spread over the course of the day, this total power deficit is relatively minimal and is already calculated into the graphic above.

2.2.8 Prototype conclusions

As a whole, the aspects of this project fit together well. It fulfils most of the required criteria. It is efficient, portable, user friendly and cost effective. It was not as portable as it was planned to be but this was partially compensated for by the larger energy gathering capabilities provided by the two-panel design. The design proved to be very sturdy and durable.

Due to the size and output capabilities of the prototype it may be better suited to use as a semi-permanent solar power source as opposed to a fully portable system.

2.2.9 Prototype recommendations

Alterations that would be beneficial to this prototype are the addition of a fuse and a method of collapsing the structure further in order to increase portability.

2.3 Prototype 3

2.3.1 Preliminary Design Procedure

2.3.1.1 Mechanical

To improve on prototypes 1 and 2 it was decided that a design is needed that allows for easy transportation without risk of damaging the system. The solution was to build the system into its own travel case. To do this the rotational movement of the panel was removed and replaced by a second tilt axis. This will allow the tracking mechanism to take up less space while maintaining stability.

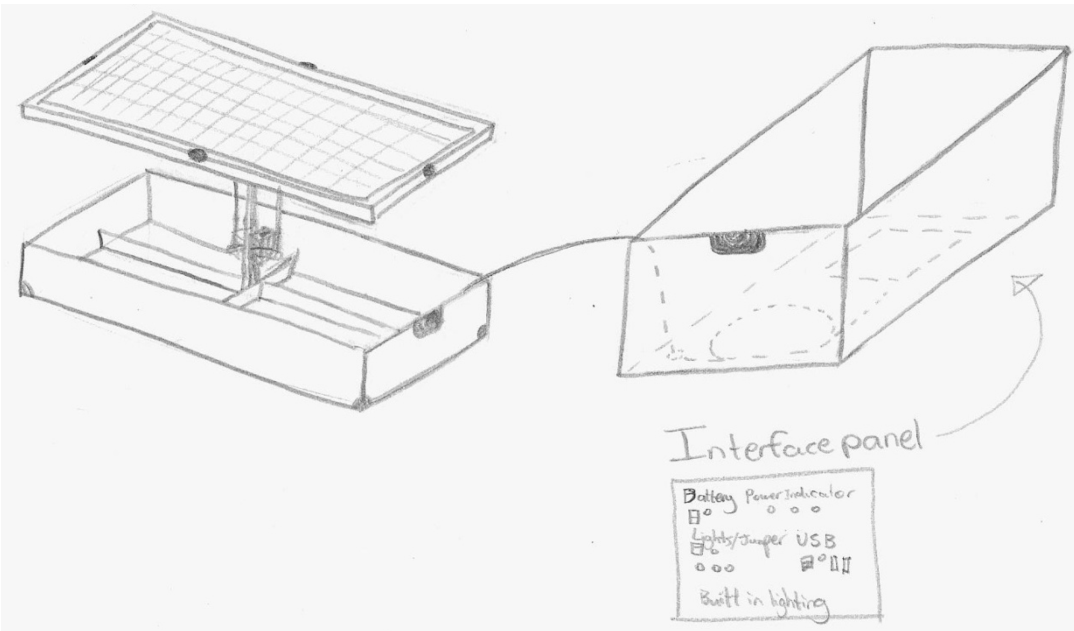


Figure 60: Prototype 3 Preliminary design

Note:
The interface panel would be built into the lid of the box.
A handle would be attached on top of the lid.
A strong clip would be fixed on both sides of both the lid and the base.
The photovoltaic panel would be attached to the vertical support via a universal joint.
The two tilt axes would be controlled with two servo motors.

2.3.1.2 Electronic

This prototype would require different circuitry to the previous two prototypes.
Servos would be used as opposed to motors, allowing for more precise tracking and allowing the program to reset the panel to certain positions.

Two smaller batteries would be used as opposed to a single large battery as this allows for a more even weight distribution.

Since motors were not going to be used, the motor driver circuit board was no longer necessary.
The easiest solution would be to use the programmable hobbyist computer circuit on its own.
It can control the servos and can read all the different sensor values simultaneously.

2.3.1.3 Programmed

As this prototype uses servos the program would differ greatly from the previous two prototypes. The servos allow for very precise tracking. They are also able to reset to pre-programmed locations. This allows for the possibility of stabilizing the panel when light levels are too low to charge the batteries.

2.3.2 Development

2.3.2.1 Mechanical

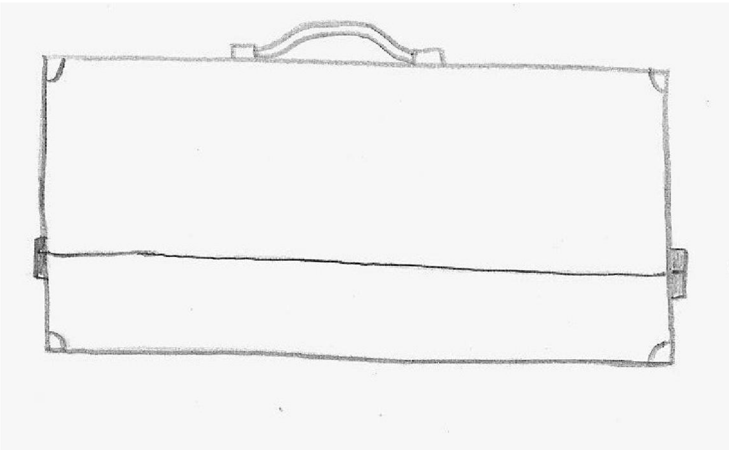


Figure 61: Prototype 3 Casing closed

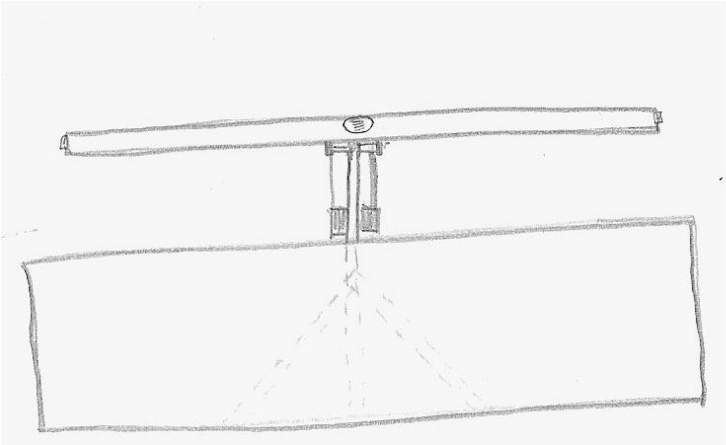


Figure 62: Prototype 3 Casing open

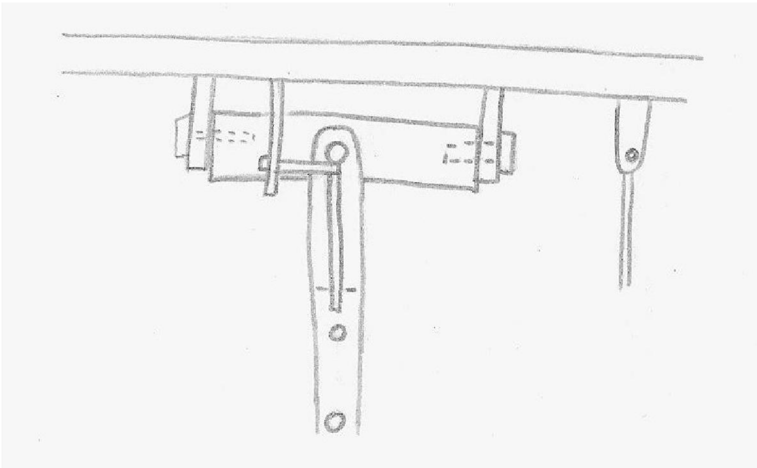


Figure 63: Prototype 3 Universal joint front view

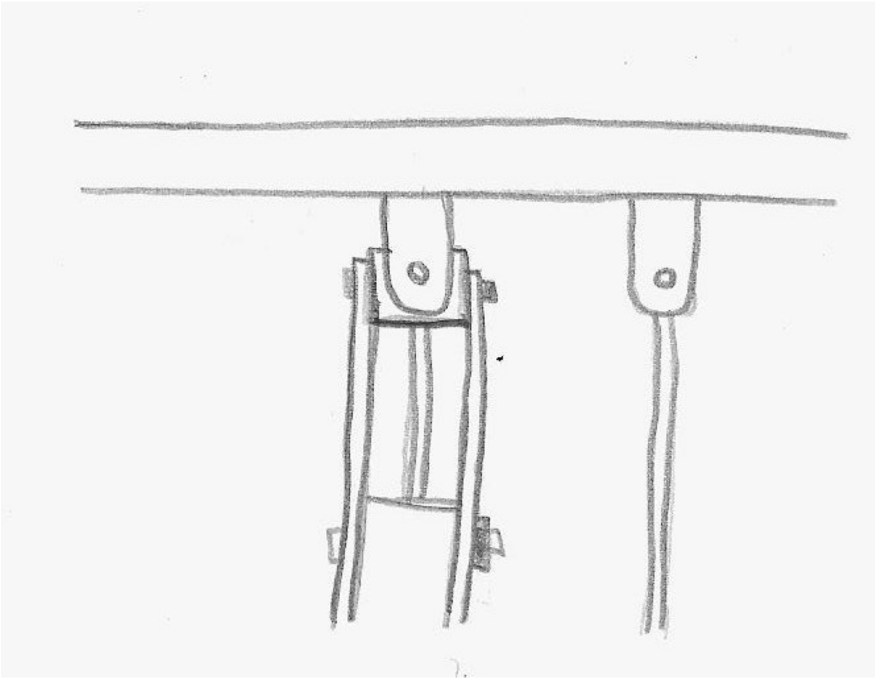


Figure 64: Prototype 3 Universal joint side view

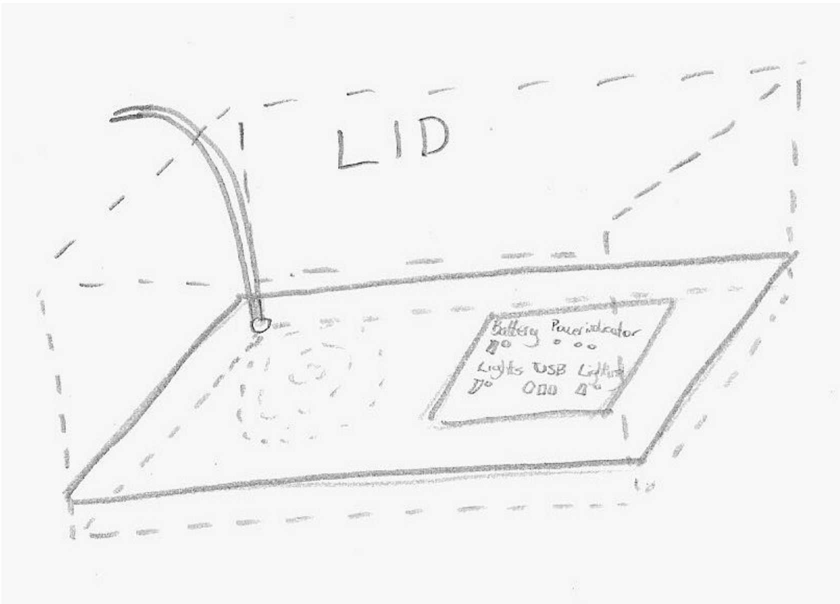


Figure 65: Prototype 3 Lid containing user interface

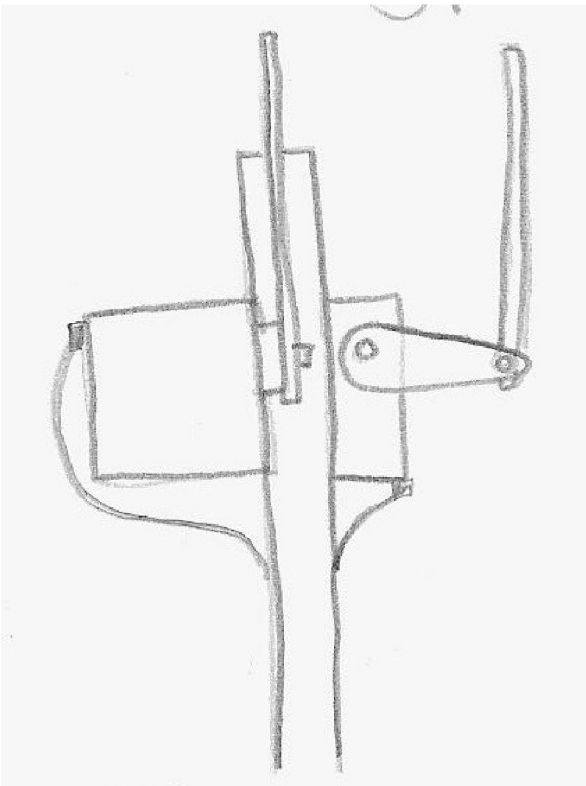


Figure 66: Prototype 3 Servo motor mounts

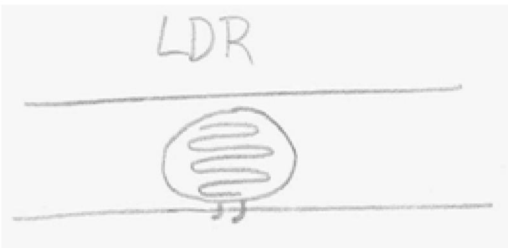


Figure 67: Prototype 3 LDR mount

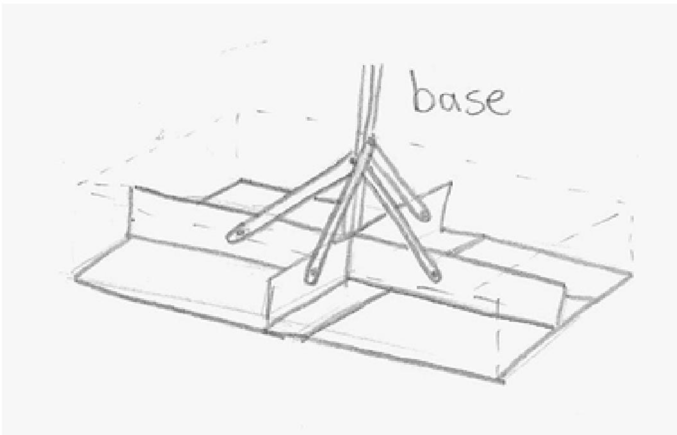


Figure 68: Prototype 3 Base support

Below is a list of the resources required:

- 7,5 m Angled aluminium 19 x 2 mm square
- 1 m Angled aluminium 38 x 2 mm square
- 2,5 m Flat bar aluminium 25 x 2 mm
- 22x M4 x 12 mm Bolts
- 7x M4 x 30 mm Bolts
- 8x M4 Washers
- 500 x 500 x 1 mm PVC sheet plastic
- 4x M3 x 16 mm Bolts
- 124x 4mmx 8mm pop rivets
- 22x 4mmx 15mm pop rivets
- 2x medium butterfly clips
- 8x speaker corner pieces

The following process was used to construct the prototype:

Lid:
- Cut sheet plastic into the correct sized pieces.
- Cut angle aluminium to the correct lengths.
- Bevelled all corners of the angle aluminium to allow them to fit into each other at the corners.
- Drilled holes through the aluminium and the sheet plastic and riveted them together.
- Added angled aluminium to the vertical edges for strength.
- Added diagonal bracing of flat bar aluminium.
- Cut plastic control panel sheet to the correct size and drilled support holes.
- Fitted the control panel sheet into the lid and attached using nuts and bolts.
- Attached internal supports for handle.
- Attached handle.
- Attached clip to short side.

Panel base and panel attachment:
- Cut sheet plastic into the correct sized pieces.
- Cut angle aluminium to the correct lengths.
- Bevelled all corners of the angle aluminium to allow them to fit into each other at the corners.
- Drilled holes through the aluminium and the sheet plastic and riveted them together to form a box.
- Added angled aluminium to the vertical edges for strength.
- Attached angled aluminium bar to base to be used for panel support.
- Attached panel central support to angled bar.
- Attached struts from panel central support to various points to act as bracing.
- Attached clip grip to short side.

Panel framework:

- Cut 3 wide aluminium flat bars to appropriate length.
- Bent them to form a step.
- Holes were drilled into the ends and through the aluminium edge on the solar panel.
- Holes were drilled through the end of the shorter bars.
- Holes were drilled through the centres of the shorter bars.
- Holes were drilled through the longer bar where the short bars' holes line up.
- The shorter bars were bolted to the longer bar.
- The bars were bolted to the panel.

Universal Joint:

- Square bar was cut to appropriate length (10cm).
- A hole was drilled through the long side in the centre (horizontally and vertically).
- Holes were drilled into the two ends also in the centre.
- The larger angle aluminium was cut into two narrow pieces.
- Holes were drilled through the tops of both and two holes along the base of both at equal spacing.
- Bolts were put through the top holes and nuts were tightened onto the other side. (both)
- A washer was placed on both and then the extended bolts ends were inserted into the holes at the ends of the bar.

Attaching the universal joint to the solar panel framework:

- The entire universal joint was placed, centred on top of the panels framework and holes were drilled where the holes of the universal joint base were.
- The universal joint was bolted to the framework.

Attaching the universal joint to the single column:

- Two strips of aluminium were cut and bolted to either side of a square bar extending further than the square bar.
- Holes were drilled in the ends and the universal joint is placed in between these strips and a bolt is slotted through everything.

Vice grip modification:

- The vice grip that was used has metal grips that can create scratches and small dents on the aluminium being worked with. Therefore a solution was devised where two small plastics sheets were cut out and duct taped to the vice grip to keep the aluminium looking new.

Counter-balance system:

- Thin strip aluminium was cut to length and bent by 90 degrees near the end.
- Two holes were drilled in the now short end and a single hole is drilled near the end of the ling end.
- Two lead sinkers were attached, one either side of the long end and a bolt held this all together.
- Two of these were made.
- The short side was then attached to the panel framework at quarter lengths.

Servo mounts:

- Short pieces of angle aluminium were cut to length and a part was cut out of a side. A hole is drilled either side of this gap and a servo is attached like this.
- On the other part of the piece two more holes were drilled and bolts were put through the central support column to attach the servos.

Attaching the servos to the panel framework via pushrods:

- Hex Honeycomb aluminium bar was cut to length and grinded flat on both ends.
- Holes were drilled through the flat sides.
- The one end was bolted to servo arm.
- The other was bolted to the bottom horizontal bar of the universal joint.
- The other arm was attached with a ball joint on one end to the servo arm and to the panel framework along the other axis to the first push/pull rod via another very small universal joint.

Programmable hobbyist computer:

- A simple example of a program was used to understand how programmable hobbyist computer interacts with the servo motors.
- The first test was sending the servo a certain position.
- Then a simple program was written to control the position using a single LDR.
- Then a comparative aspect was added to determine the direction of rotation.
- A dead zone was added to prevent the servo from moving so frequently.
- This was duplicated for each channel of servo and LDR's.
- All values in the program were replaced with variables, defined at the start of the program.
- A stepping increment was added to slow down and increase the accuracy of the movement.

Battery mounts:

- Large angle aluminium was cut to shorter lengths and riveted to the base on three sides of the batteries, pinning the batteries to the sides of the lower box.

Battery covers:

- Sheet plastic was cut into a rectangle larger than the battery.
- Rectangles were cut out from the two end corners.
- The three sides adjacent to the cut-outs were the heated with a heat gun and then bent 90 degrees downward.
- The non-folded sides then had a short piece of smaller angle aluminium riveted to them.
- The angle aluminium was then bolted to the side of the box to allow the covers to be taken off when accessing the battery terminals.

2.3.2.2 Electronic

Please see the electronic schematics below in order to construct the required circuitry. All components required in these schematics can be found in the following list.

- 2 x servo motors (10.50 kg-cm, 180° range)
- 2 x 12 V 7 Ah alarm battery
- 4 x LDR 50kΩ 35 V
- 2m Electrical wire solid core copper
- 5x single pole, single throw switch
- 1x pushbutton
- 2x USB port
- 3x DC power socket
- 1x Atmel AtMega168
- 1x Programmable hobbyist computer
- 2x LM323T 5 V 3 A positive voltage regulators
- 1x 5 A fuse
- 1x 2 A fuse
- 2x PB137 13,7 V 1,5 A lead acid battery charger
- 1x BC547 NPN transistor
- 1x BC557 PNP transistor
- 1x 1 µF 25 V electrolytic capacitor
- 2x 10 µF 25 V electrolytic capacitor
- 2x 1000 µF 25 V electrolytic capacitor
- 2x 470 µF 25 V electrolytic capacitor
- 4x 47 kΩ ⅛ W resistor
- 3x 220 Ω ⅛ W resistor
- 2x 1 kΩ ⅛ W resistor
- 5x 3,3 kΩ ⅛ W resistor

The regulator circuits were built on strip board and then connected to the rest of the system via loose cabling.
The hobbyist PC-on-a-board was connected to the servos and pull-down resistors via a small strip board circuit and jumper pins.
The servo motors receive power from a 5V regulator.
A power circuit is built to convert the unregulated power from the solar panels into a useable voltage to charge the batteries and provide power for the rest of the circuit.

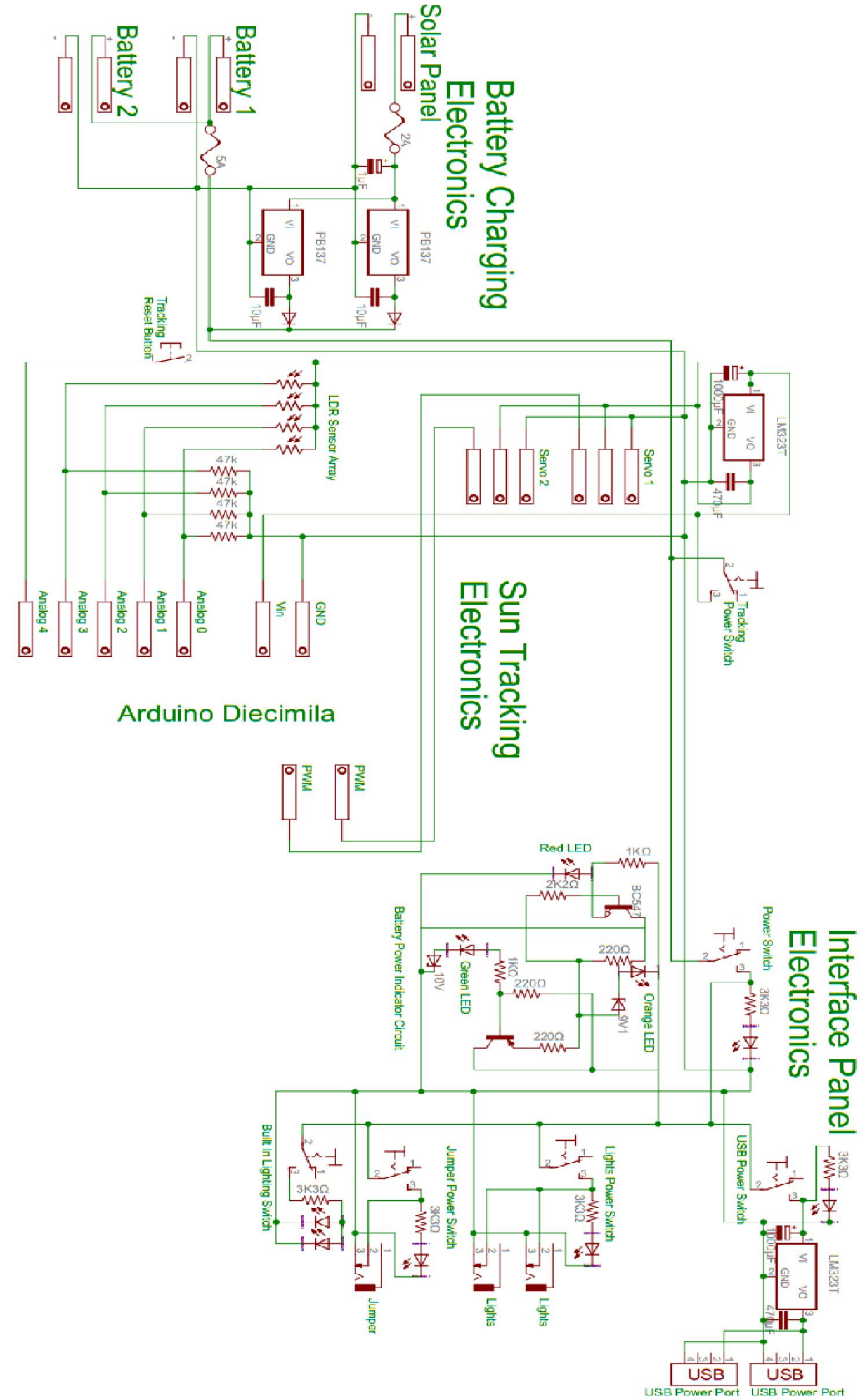


Figure 69: Prototype 3 Electronics schematic

2.3.2.3 Programmed

As this prototype uses servos the program would differ greatly from the previous two prototypes. The servos allow for very precise tracking. They are also able to reset to pre-programmed locations. This allows for the possibility of stabilizing the panel when light levels are too low to charge the batteries.

The program had to follow a certain logical pattern.

See below a sketch illustrating the logic used to create the program:

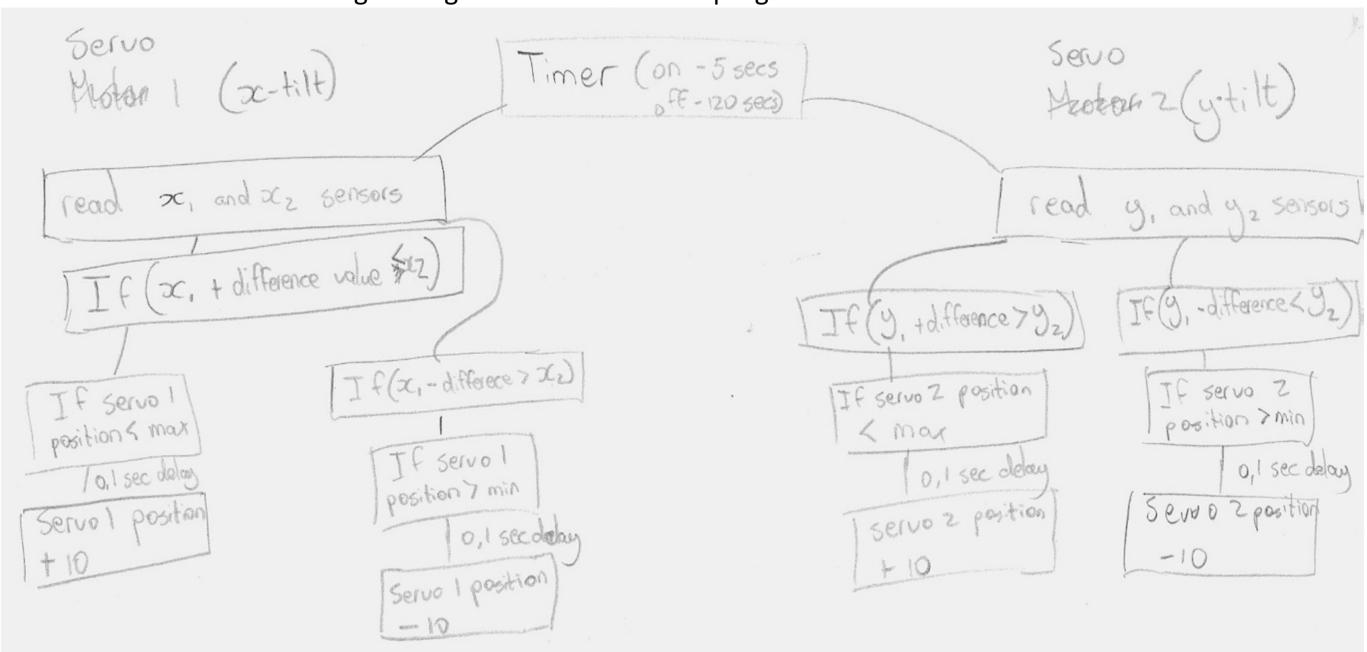


Figure 70: Prototype 3 Program logic

2.3.3 Prototype 3 Final Design

2.3.3.1 Mechanical

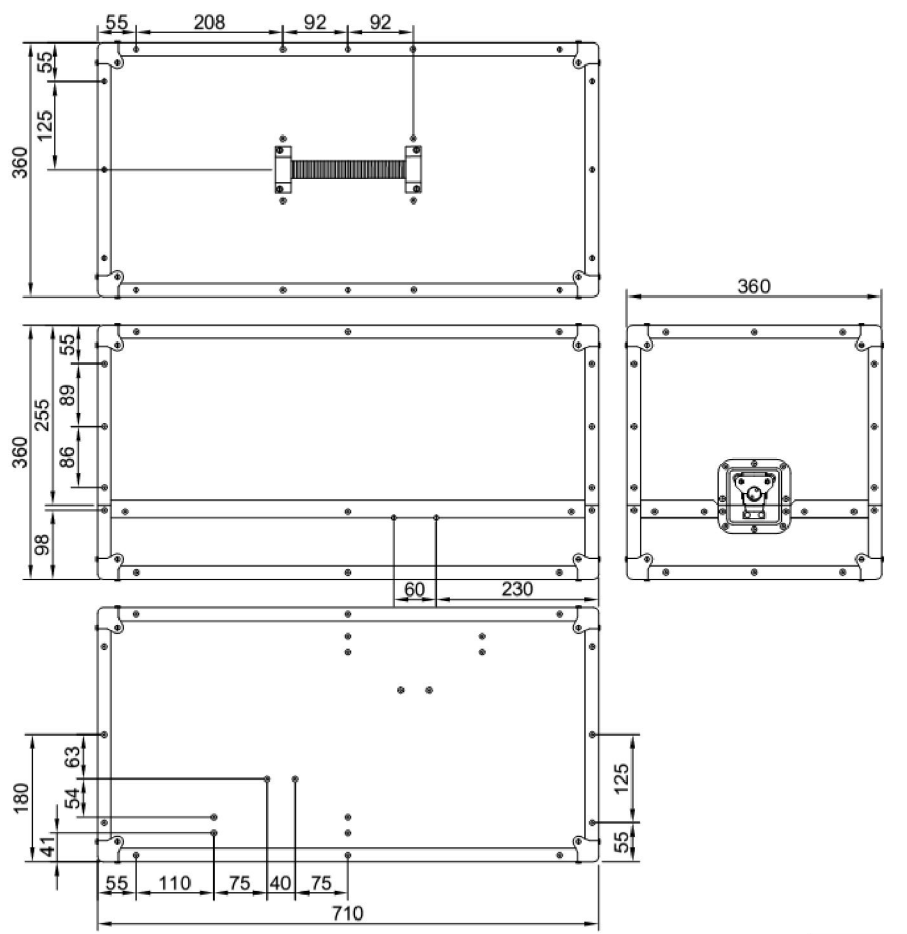
The final design closely follows the original ideas.

See below some images of the complete prototype:

Figure 71: Prototype 3 Finished look

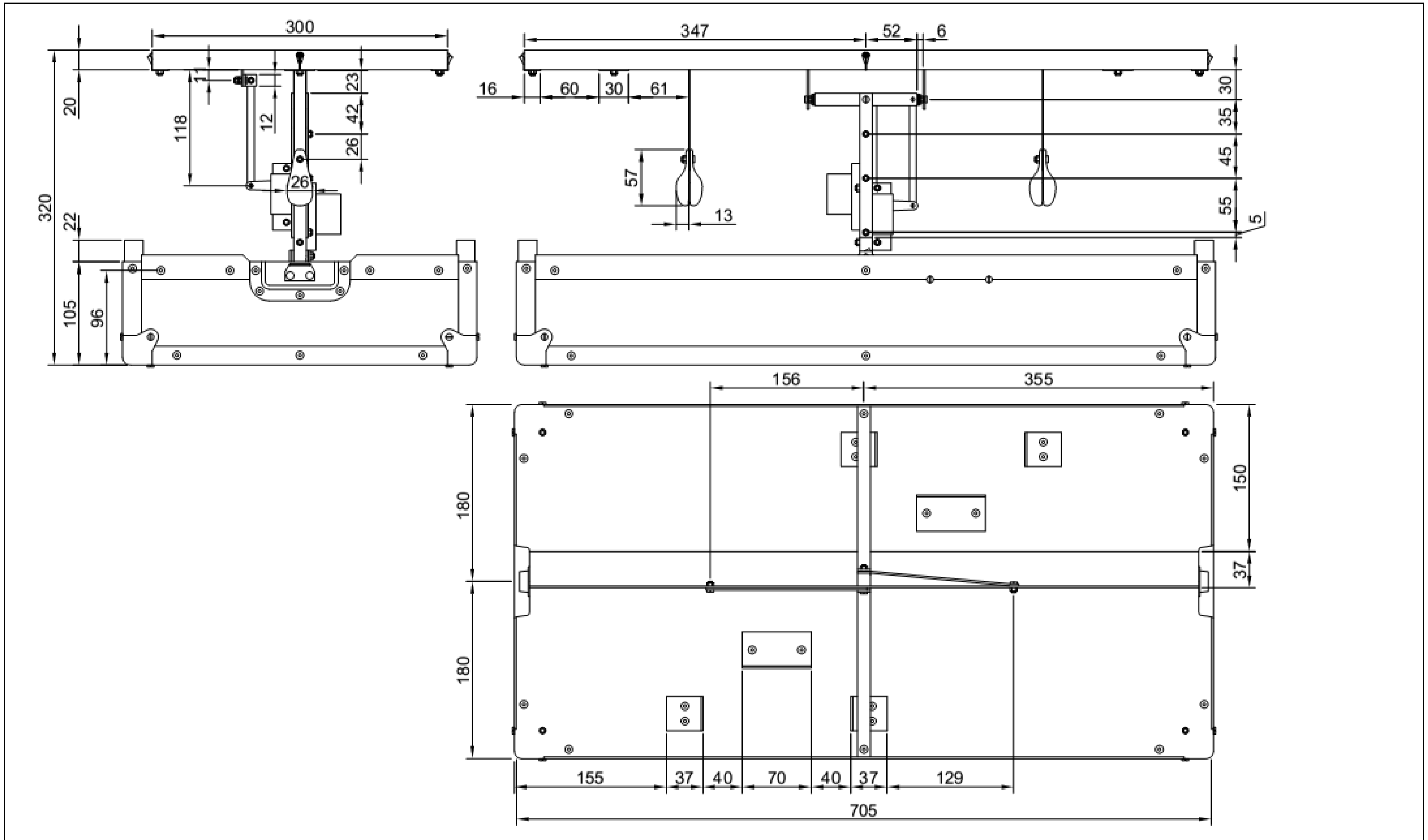
Figure 72: Prototype 3 Finished look

For details and measurements regarding construction, please see the technical drawings on the following few pages.



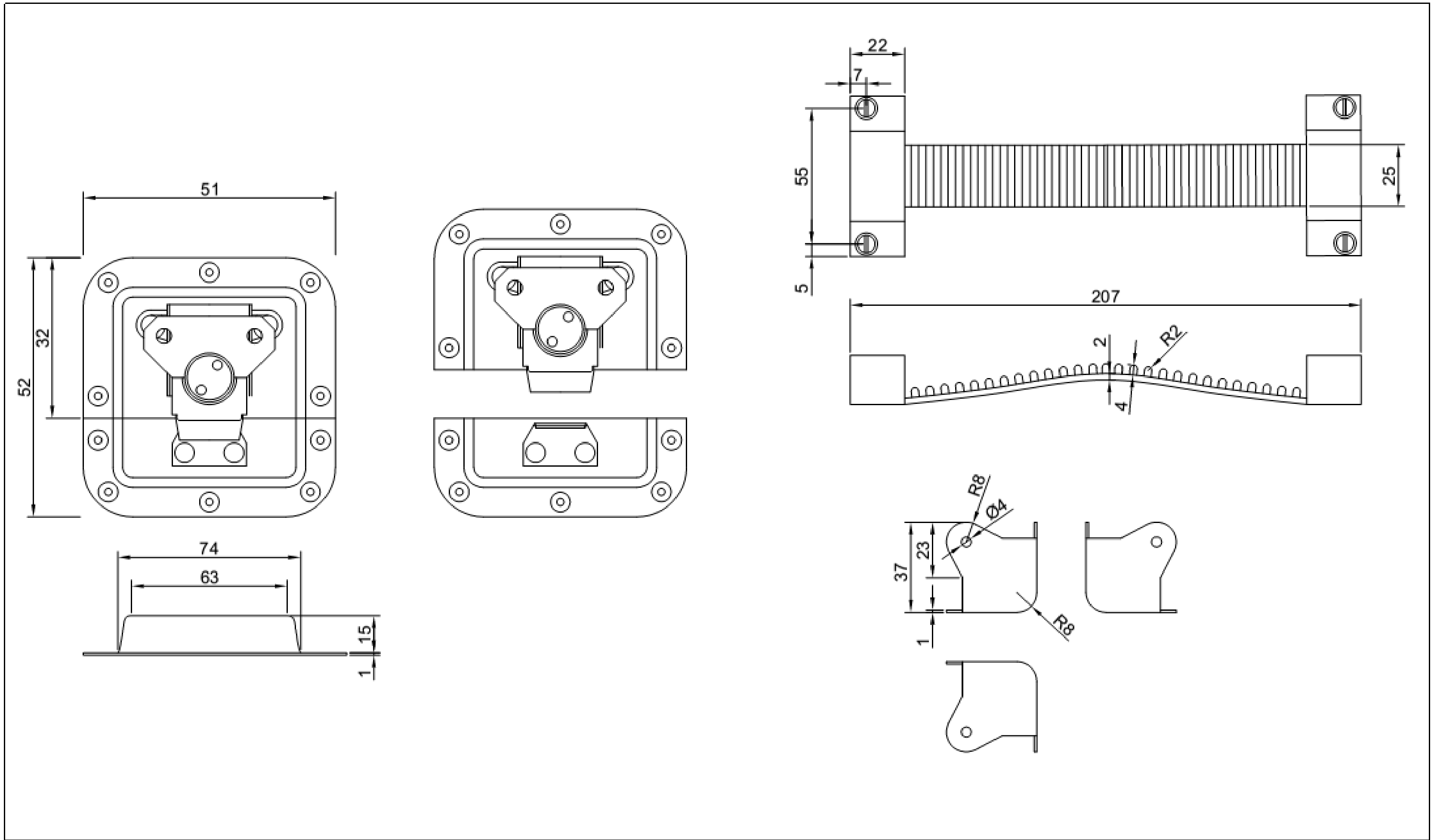
NOTES:
ALL PLASTIC AND ALUMINIUM IS 2 MM THICK UNLESS OTHERWISE SPECIFIED
ALL HOLES ARE Φ4 MM UNLESS OTHERWISE SPECIFIED

DRAWING NAME TRAVEL PACKED SYSTEM	
FILE NAME ISF 2014 MkII.dwg	
DRAWING NUMBER ISF14-2	DRAWN BY J.SENIOR
	SCALE 1:8
DRAWN 21/09/2014	PRINTED 29/08/2014



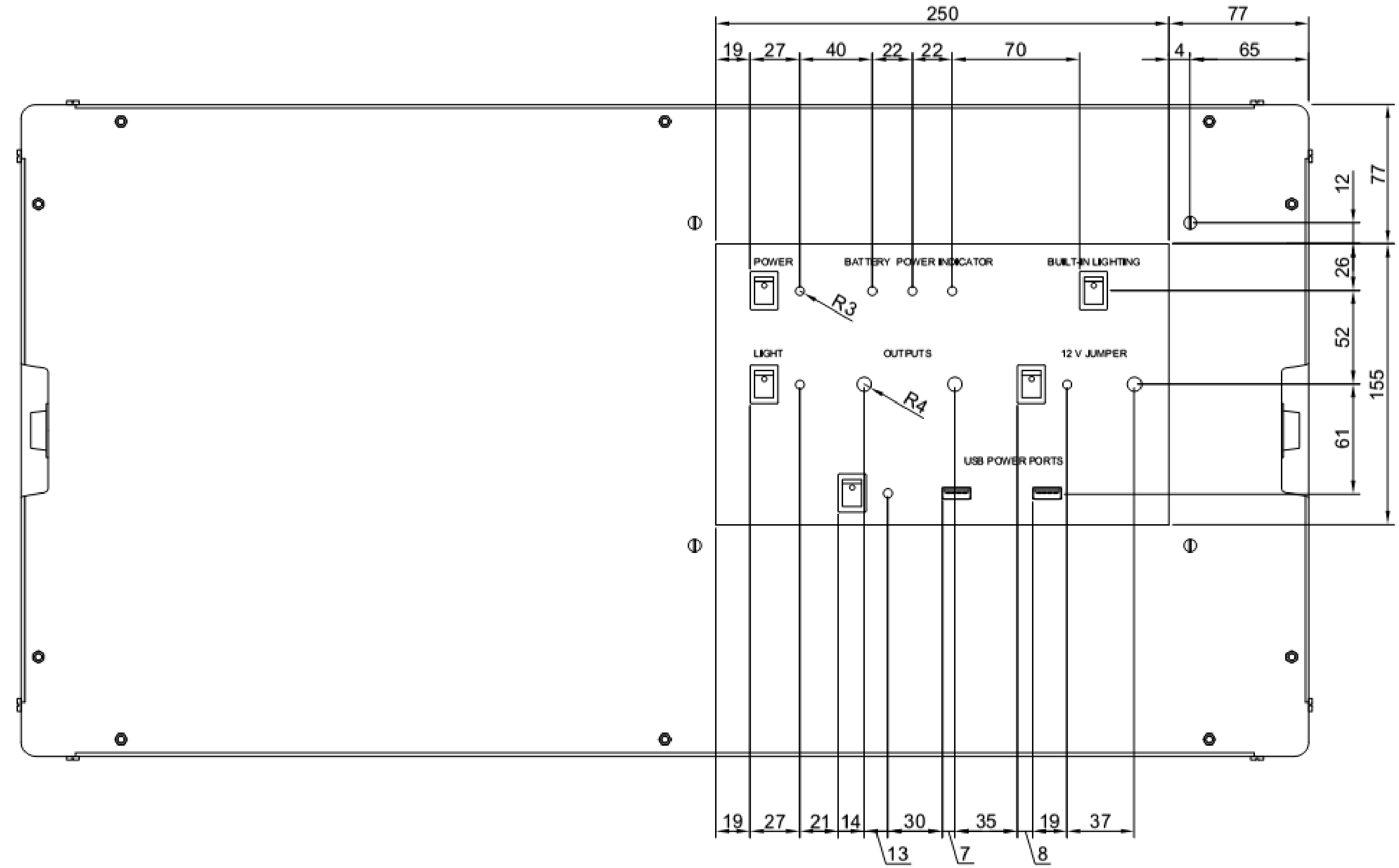
NOTES:
ALL PLASTIC AND ALUMINIUM IS 2 MM THICK UNLESS OTHERWISE SPECIFIED
ALL HOLES ARE ϕ4 MM UNLESS OTHERWISE SPECIFIED

DRAWING NAME ASSEMBLED BASE	
FILE NAME ISF 2014 MkIII.dwg	
DRAWING NUMBER ISF14-1	DRAWN BY J.SENIOR
	SCALE 1:5
DRAWN 20/09/2014	PRINTED 29/09/2014



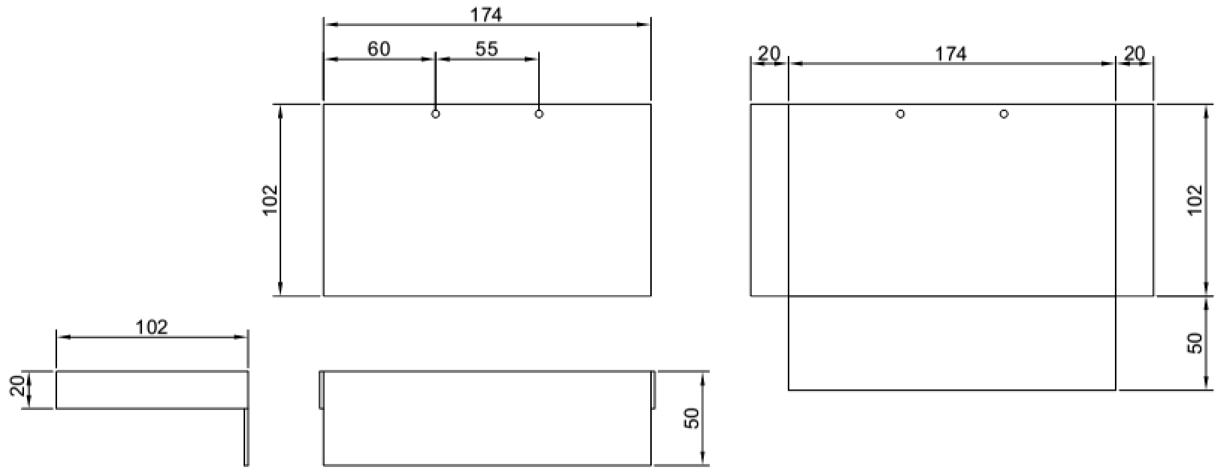
NOTES:
ALL PLASTIC AND ALUMINIUM IS 2 MM THICK UNLESS OTHERWISE SPECIFIED
ALL HOLES ARE Ø4 UNLESS OTHERWISE SPECIFIED

DRAWING NAME SMALL PARTS	
FILE NAME ISF 2014 MkII.dwg	
DRAWING NUMBER ISF14-3	DRAWN BY J.SENIOR
	SCALE 1:2
DRAWN 27/09/2014	PRINTED 29/08/2014



NOTES:
ALL PLASTIC AND ALUMINIUM IS 2 MM THICK UNLESS OTHERWISE SPECIFIED
ALL HOLES ARE Ø4 UNLESS OTHERWISE SPECIFIED
LABELS ARE TO BE CENTERED ABOVE OUTPUT/ SWITCH
TEXT IS LASER ETCHED INTO PERSPEX PANEL SURFACE. ALL PERSPEX IS LASER CUT.

DRAWING NAME	INTERFACE PANEL		
FILE NAME	ISF 2014 MkII.dwg		
DRAWING NUMBER	ISF14-4	DRAWN BY	J.SENIOR
		SCALE	1:3
DRAWN	27/09/2014	PRINTED	29/08/2014



NOTES:
ALL HOLES ARE 4MM UNLESS OTHERWISE SPECIFIED
THIS COVER IS MOLDED FROM A SHEET OF PLASTIC

DRAWING NAME	BATTERY COVERS		
FILE NAME	ISF 2014 MkII.dwg		
DRAWING NUMBER	ISF14-5	DRAWN BY	J.SENIOR
		SCALE	1:3
DRAWN	27/09/2014	PRINTED	29/09/2014

3.3.3.2 Electronic

Four Light Dependent Resistors (LDRs) were used in series with a 47 kΩ each. These resistors each connect to 0 V, effectively causing the voltage to lower. The other leg of each of the LDR's connects to the 5 V output on the PC-on-a-board. The leg that it connected to the resistor is then connected to a analogue input on the PC-on-a-board. The LDR's are attached in the middle of each edge of the photovoltaic panel with the use of glue. The LDR's are bent to face outwards at an angle of 120° made from the front face of the LDR and the side of the photovoltaic panel framework. The LDR's are bent like this to enable them to detect light in any direction.

Two 5 V servo motors are powered by 5 V 3 A regulator. The signal of each respective servo motor is connected to the "PWM" (standing for Pulse Width Modulation) output pins on the PC-on-a-board.

The interface panel has a power lead connecting the batteries in parallel via diodes. The power lead is connected to the power rail via a switch labelled "POWER".

The power rail is directly connected to a battery indicating circuit. This circuit has three different coloured Light Emitting Diodes (LED's): Red, Yellow and Green. The red LED will light up if the input voltage is 5 V or higher. The yellow will light up from 11 V and upwards. The green LED will only light up if the voltage is 13.7 V or higher. 13.7 V is the specific voltage that 12 V lead acid battery will have when it is fully charged. The yellow LED will indicate that the batteries still have enough voltage to be used, but caution should be taken. If only the red LED is lit up, the batteries require charging and using the outputs is advised against.

There are a series of two 12 V DC sockets that are connected to the power rail via a single switch. The sockets are designed to be used for two LED lights. There is also a single 12 V DC socket that is directly connected to the power rail via a switch. This single socket is designed to be used in conjunction with the jumper cable. The jumper cable has a corresponding plug to the socket on the one end and crocodile clips on the other. This jumper cable is used to charge 12 V batteries or power other 12 V devices that have exposed terminals.

There are two Universal Serial Bus (USB) ports that have 5 V of regulated power from the power rail via a switch. These USB ports can be used to charge or power cell phones or any other devices that can be charged using 5 V USB power.

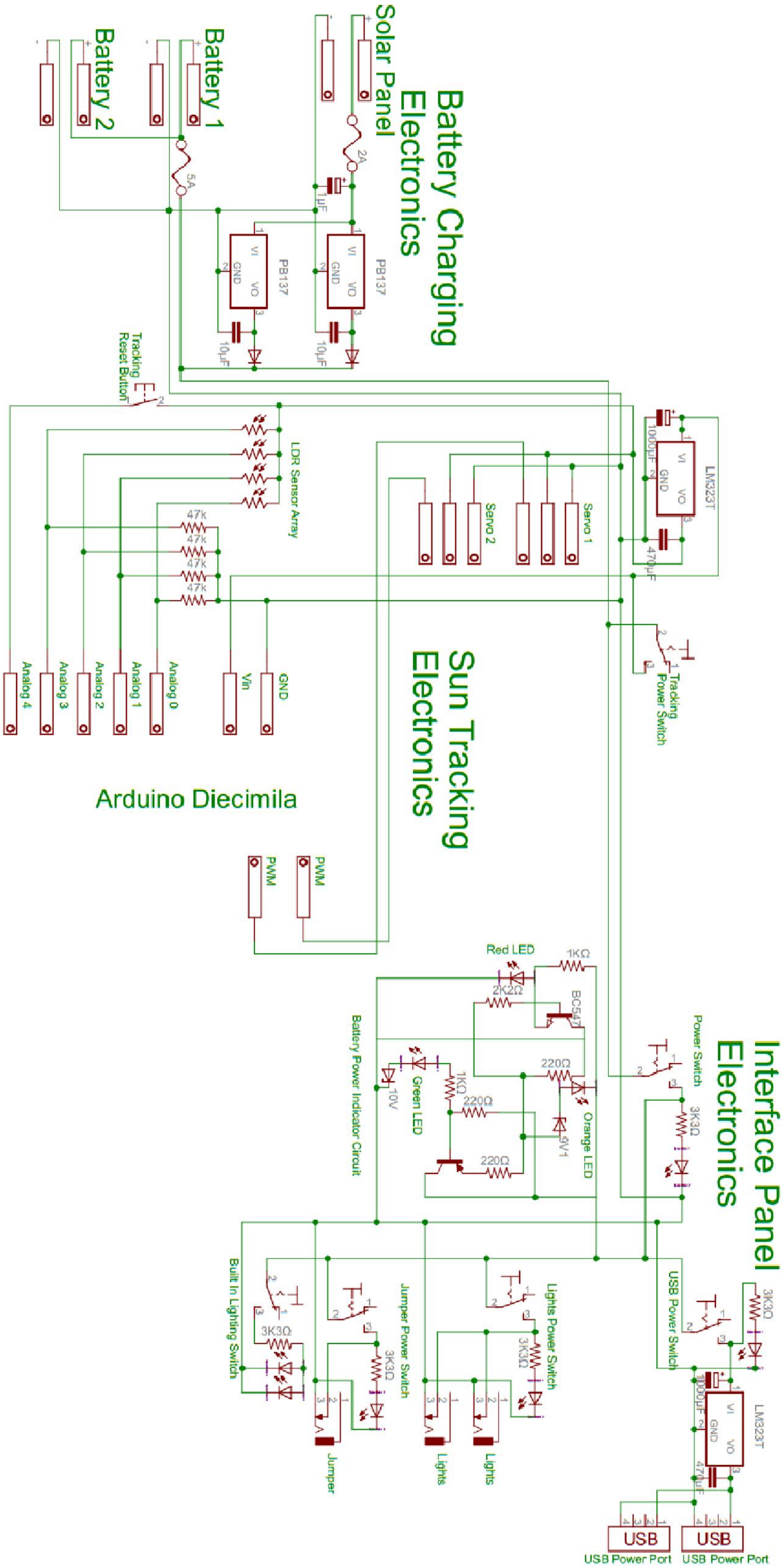


Figure 73: Prototype 3 Electronics schematic

2.3.3.3 Programmed

A hobbyist PC-on-a-board was used. The PC-on-a-board has its own programming language and USB programming interface. Programming allows things to become extremely easily customized. It is very easy to implement sun tracking algorithms and modify them as needed. It is also relatively easy to add in extra features and safety mechanisms that would have been very difficult to implement with standard electronics. Safety measures include limiting the angle of the solar panel and limiting the speed at which the solar panel can rotate to prevent damage to itself and other mechanical constructions. All of above justifies the use of a programmable circuit board.

This program in effect causes the solar panel to turn to face the sun perpendicularly in the sky. It cannot tilt too far in any direction and is limited to a 120° range of rotation. It resets to home position if the total light level is too low for the solar panel to be generating any power.

This is the code for the active tracking system:

```
#include <Servo.h>

Servo servo1;
Servo servo2;

float pos1 = 90;
float pos2 = 90;

int deadzone1 = 15;
int deadzone2 = 10;
int center1 = 90;
int center2 = 90;

int servo1Max = 115;
int servo1Min = 50;
int servo2Max = 150;
int servo2Min = 60;
float servoStep = 1;

boolean offButton = false;
boolean offFloppy = false;

int darkLevel = 200;
boolean darkFloppy = false;

int onTime = 1000;
int offTime = 65535;
int timeCounter = 0;

// the setup routine runs once when you press reset:
void setup() {
 // initialize serial communication at 9600 bits per second:
 Serial.begin(9600);

 servo1.attach(9);
 servo2.attach(10);
}

// the loop routine runs over and over again forever:
void loop() {
		// read the input on analog pin 0:
		int sensorValue1 = analogRead(A0);
		int sensorValue2 = analogRead(A1);
		int sensorValue3 = analogRead(A2);
		int sensorValue4 = analogRead(A3);
		offButton = digitalRead(A4);

		timeCounter ++;
```

```
if (timeCounter >= offTime)
{
        timeCounter = 0;
}

if (timeCounter < onTime)
{



        if (offButton == true)
        {
                offFloppy = true;
        }


        if (sensorValue1 < darkLevel && sensorValue2 < darkLevel && sensorValue3 < darkLevel && sensorValue4 < darkLevel)
        {
                darkFloppy = true;
        }
        else
        {
                darkFloppy = false;
        }

        if (sensorValue1 > sensorValue2 + deadzone1)
        {
                pos1 += servoStep;

        }
        else if (sensorValue1 < sensorValue2 - deadzone1)
        {
                pos1 -= servoStep;

        }
        if (sensorValue3 > sensorValue4 + deadzone2)
        {
                pos2 += servoStep;

        }
        else if (sensorValue3 < sensorValue4 - deadzone2)
        {
                pos2 -= servoStep;

        }

        if (pos1 >= servo1Max)
        {
                pos1 = servo1Max;
        }

        else if (pos1 <= servo1Min)
        {
                pos1 = servo1Min;
        }

        if (pos2 >= servo2Max)
        {
                pos2 = servo2Max;
        }

        else if (pos2 <= servo2Min)
        {
                pos2 = servo2Min;
        }

        if (offFloppy == true)
        {
                if (pos1 < center1 -(2 * servoStep))
                {
                        pos1 += 2 * servoStep;
                }
                else if (pos1 > center1 +(2 * servoStep))
                {
```

```
                    pos1 -= 2 * servoStep;
                }
                else
                {
                     pos1 = center1;
                }

                if (pos2 < center2 - (2 * servoStep))
                {
                    pos2 += 2 * servoStep;
                }
                else if (pos2 > center2  + (2 * servoStep))
                {
                    pos2 -= 2 * servoStep;
                }
                else
                {
                     pos2 = center2;
                }
            }

            if (darkFloppy == true)
            {
             if (pos1 < center1 -(2 * servoStep))
             {
                    pos1 += 2 * servoStep;
             }
             else if (pos1 > center1 +(2 * servoStep))
             {
                    pos1 -= 2 * servoStep;
             }
             else
             {
                    pos1 = center1;
             }

             if (pos2 < center2 - (2 * servoStep))
             {
                     pos2 += 2 * servoStep;
             }
             else if (pos2 > center2  + (2 * servoStep))
             {
                     pos2 -= 2 * servoStep;
             }
             else
             {
                     pos2 = center2;
             }
        }
        }


         // print out the value you read:
        Serial.print("1: ");
        Serial.print(sensorValue1);
        Serial.print("    2: ");
        Serial.print(sensorValue2);
        Serial.print("    3: ");
        Serial.print(sensorValue3);
        Serial.print("    4: ");
        Serial.print(sensorValue4);
        Serial.print("    pos1: ");
        Serial.print(pos1);
        Serial.print("    pos2: ");
        Serial.print(pos2);
        Serial.print("    offFloppy: ");
        Serial.println(offFloppy);

        servo1.write(pos1);
        servo2.write(pos2);

        delay(25);       // delay in between reads for stability
}
```

2.3.4 Prototype Evaluation

2.3.4.1 Mechanical Computer-Aided Design (CAD) drawings

The mechanical aspect of the system ran smoothly. The design functioned as intended with no notable flaws. It is effective at tracking the sun. It is not, however, as portable as it could be. Due to the materials it is too heavy to be carried comfortably.

Some minor adjustments were made while testing to balance the weight of the photovoltaic panel in order to reduce the load on the servo motors.

2.3.4.2 Electronic

The electronics functioned as planned. There were no issues while testing.

2.3.4.3 Programmed

The program was effective. A notable feature was the ability to reset the panel to home position when light levels dropped below a useful level. This prevented the prototype from aimlessly moving at night.

3 Testing

The final prototype was tested using a data logger.
The final prototype was tested alongside a stationary panel for comparison purposes.

A circuit was designed and built to provide the testing load. The circuit uses an Op-amp to adapt the load in such a way to keep the voltage across the photovoltaic panel terminals constant. This causes the current to change as the photovoltaic panel receives different amounts of solar energy.
An programmable hobbyist computer board was then connected to the circuit in such a way that it could measure the voltages at different points in the circuit. These voltages would be used to calculate current, voltage and power.
The programmable hobbyist computer board would be programmed to send the values it measures to a PC.
On the PC, the values sent by the programmable hobbyist computer board would be received and recorded.
The recorded data would then be graphed and converted into useful information.

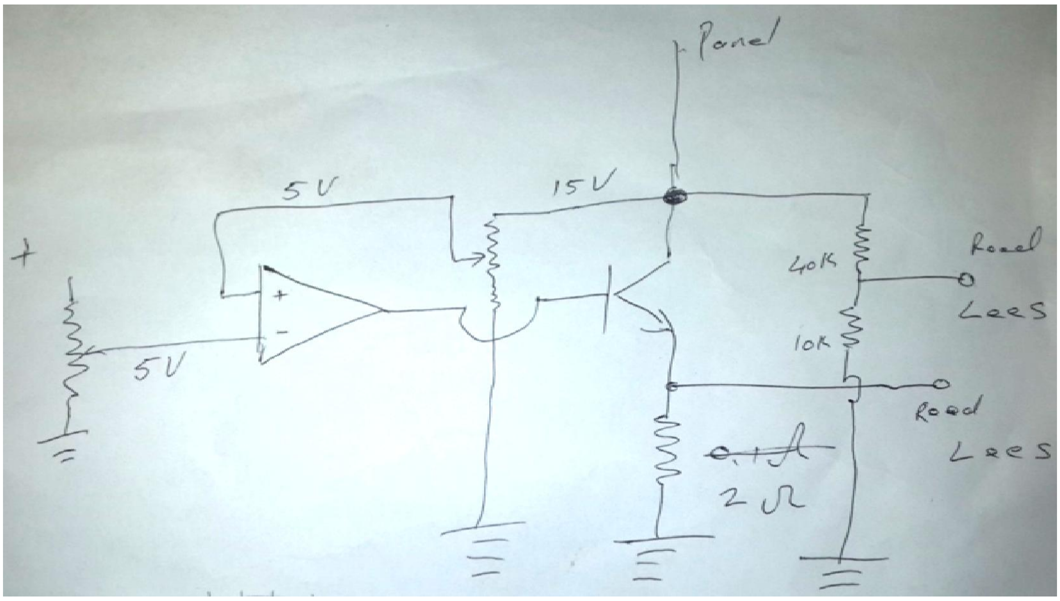


Figure 74: Prototype 3 Testing load circuit schematic

Above is the sketched schematic of the load circuit. Two were built and were tested and calibrated. The two were within 50 mV of each other, which is a reasonable degree of accuracy and can the voltage fluctuations in calibration can be explained as an imperfection of the multi meter used to test and calibrate the circuits.

The transistors facilitate a large amount of current. As a result, they get very hot. To prevent damage, they were connected externally and were bolted without any electrical connection to a large heat sink with a small fan blowing air across.

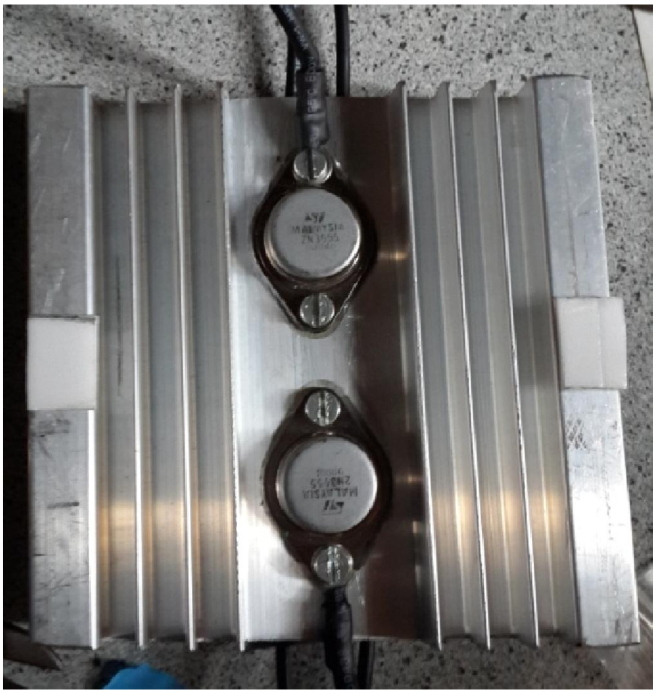


Figure 75: Prototype 3 Testing transistor heat sink

Figure 76: Prototype 3 Testing transistor heat sink and fan

The resistors in each circuit get very hot for the exact same reason as the transistors. The solution, to prevent damage was to attach heat sinks.

Figure 77: Prototype 3 Testing resistor heat sinks

The 5 V regulator powering the circuit also had a heat sink attached for safety.

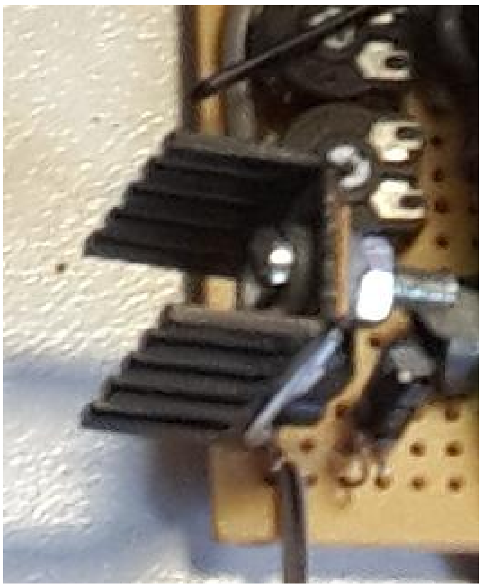


Figure 78: Prototype 3 Testing 5 V regulator with heat sink

All the circuits were attached via non-conductive double sided tape to a small plank. This was to prevent the cables from moving about during testing.

Another small fan was attached to the plank to move air across and over all the circuits. This is in order to create an airflow to keep cool fresh air cooling the system.

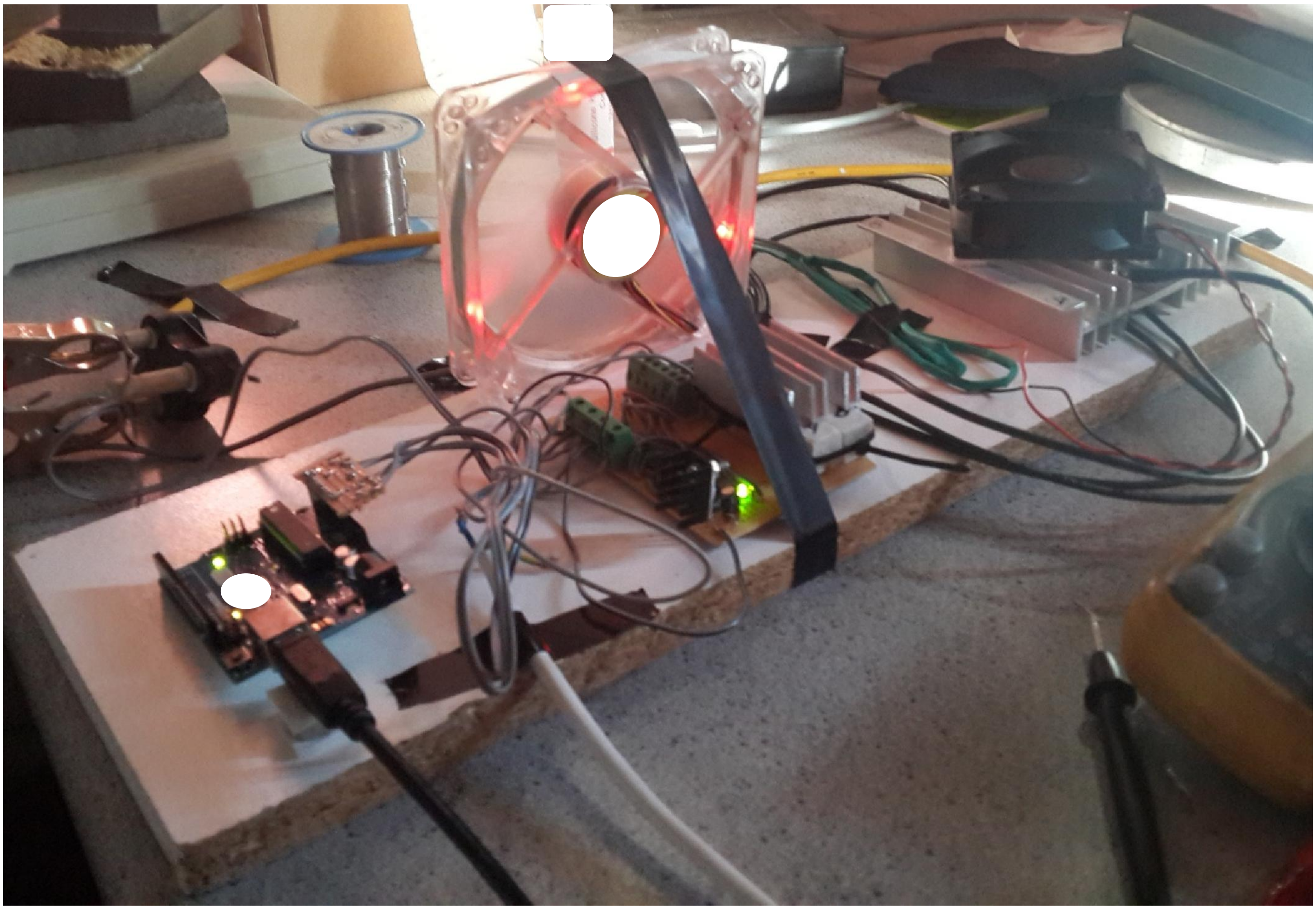


Figure 79: Prototype 3 Testing setup

The hobbyist PC-on-a-board was attached in the following way to the load circuits:

- Prototype 3: The total circuit voltage after the voltage divider network is attached to pin A0.
- Prototype 3: The voltage measured across the resistor is attached to pin A1.
- Stationary Panel: The total circuit voltage after the voltage divider network is attached to pin A2.
- Stationary Panel: The voltage measured across the resistor is attached to pin A3.
- The ground was made common with the programmable hobbyist computer and the load circuits

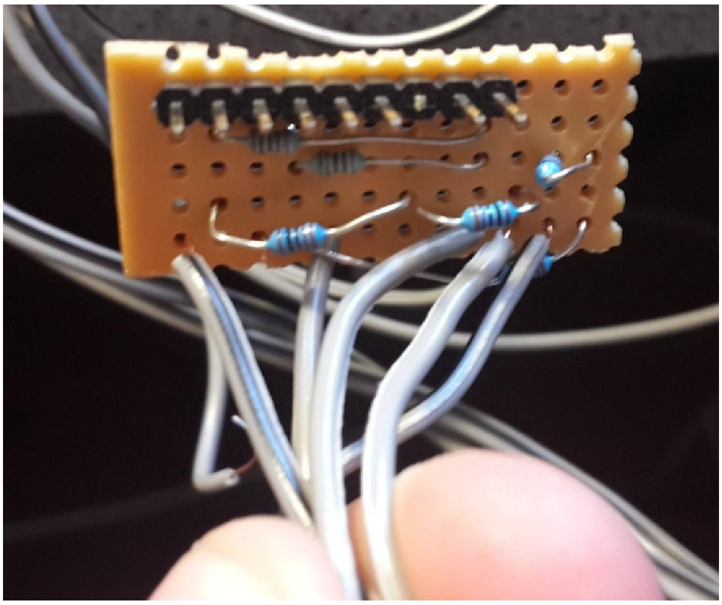


Figure 80: Prototype 3 Testing programmable hobbyist computer connection with voltage dividers

The programmable hobbyist computer board is connected to a PC via a USB cable.

Figure 81: Prototype 3 Testing programmable hobbyist computer USB cable

Provided below is a copy of the programmable hobbyist computer code:

```
int counter = 0

void setup() {
  Serial.begin(9600);

}

void loop() {


float aVolt = analogRead(A0);
float aCurr = analogRead(A1);
float bVolt = analogRead(A2);
float bCurr = analogRead(A3);

counter ++;

Serial.print(counter);
Serial.print(",");
Serial.print(aVolt);
Serial.print(",");
Serial.print(aCurr);
Serial.print(",");
Serial.print(bVolt);
Serial.print(",");
Serial.println(bCurr);

delay(10000);

}
```

Simply the programmable hobbyist computer board initiates communication with the serial connection, which in this case is the USB cable.
Every loop the programmable hobbyist computer reads the values from the inputs and then sends them directly via the serial connection.
At the end of each loop there is a 10000 ms delay, meaning that the loop will run through once after the 10 second delay. The program runs through extremely quickly, so in effect the program reads and sends values every 10 seconds.

On the PC a program is used to monitor the serial input.

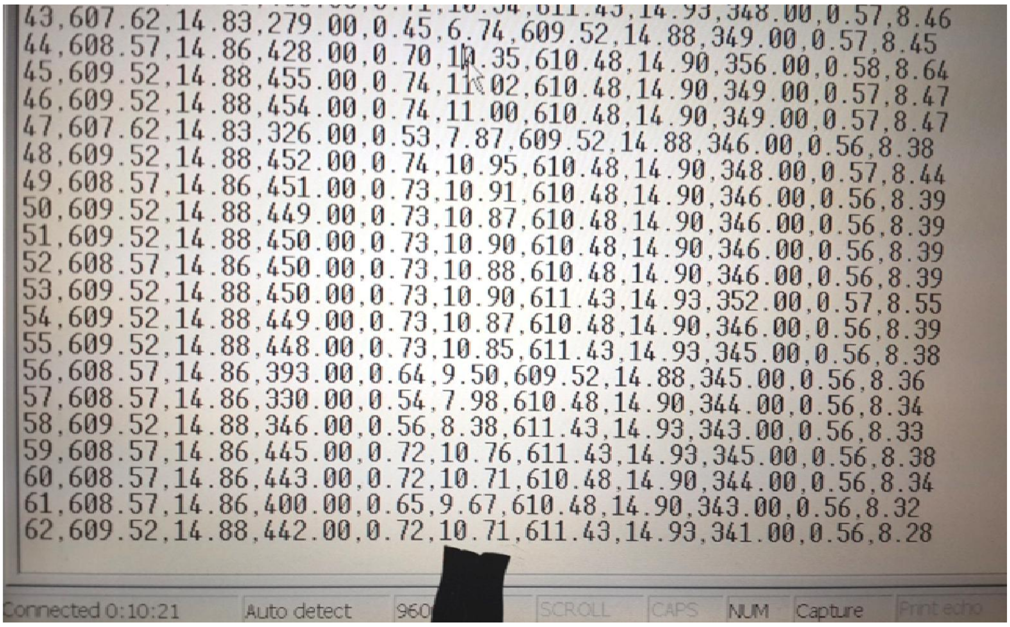


Figure 82: Prototype 3 Testing serial monitor

The same program is used to store the data to a text file. This file can be opened in a spreadsheet program as comma separated values.
The values that the programmable hobbyist computer board has sent are converted into useful quantities.
The programmable hobbyist computer reads the inputs as a value between 0 and 1023.
Therefore all saved values need to be divided by 1023 then multiplied by 5 as the range is 5 V.
This provides the original input voltage to the programmable hobbyist computer board.
Since the total circuit voltages would be too high to input to the programmable hobbyist computer board, the voltages are divided. The voltages were divided by 5, as a resistance ratio of the voltage divider was 4:1. This means that the total circuit voltages need to be multiplied by 5 again to get to the original value.
The current is then calculated by dividing the voltage across the resistor by the resistance which is known. The resistance is 2.2 Ω. These calculations are done in accordance with the following formula:

$$I = \frac{V}{R},$$

This formula is mathematical expression for Ohm's Law.
To calculate the power, at the measured time intervals, the current is multiplied by the total circuit voltage. This is in accordance with the following mathematical expression.

$$P = \text{work done per unit time} = \frac{VQ}{t} = VI$$

	Prototype 3 (Solar Tracking)					Stationary Photovoltaic Panel				
Time of Day	Raw	Voltage	Raw	Current	Power	Raw	Voltage	Raw	Current	Power
05:30:10 PM	639.996	15.6249	226.8	0.36914	5.76779	642.002	15.6739	360.15	0.586182	9.18773
05:30:20 PM	639.996	15.6249	256.2	0.41699	6.51546	642.002	15.6739	359.1	0.584473	9.16095
05:30:30 PM	641.004	15.6495	311.85	0.50757	7.9432	642.999	15.6982	359.1	0.584473	9.17518
05:30:40 PM	639.996	15.6249	186.9	0.3042	4.75308	642.002	15.6739	358.05	0.582764	9.13416
05:30:50 PM	642.002	15.6739	496.65	0.80835	12.67	642.999	15.6982	359.1	0.584473	9.17518
05:31:00 PM	642.002	15.6739	498.75	0.81177	12.7235	642.999	15.6982	359.1	0.584473	9.17518
05:31:10 PM	641.004	15.6495	378	0.61523	9.62812	642.999	15.6982	358.05	0.582764	9.14835
05:31:20 PM	643.997	15.7226	344.4	0.56055	8.81324	647	15.7959	360.15	0.586182	9.25926
05:31:30 PM	638.001	15.5762	215.25	0.35034	5.45699	639.996	15.6249	354.9	0.577637	9.02552
05:31:40 PM	641.004	15.6495	343.35	0.55884	8.74554	642.002	15.6739	357	0.581055	9.10737
05:31:50 PM	639.996	15.6249	343.35	0.55884	8.73179	642.002	15.6739	355.95	0.579346	9.08059
05:32:00 PM	638.999	15.6005	373.8	0.6084	9.49135	641.004	15.6495	354.9	0.577637	9.03973
05:32:10 PM	639.996	15.6249	355.95	0.57935	9.05222	641.004	15.6495	353.85	0.575928	9.01299
05:32:20 PM	638.999	15.6005	246.75	0.40161	6.26536	639.996	15.6249	352.8	0.574219	8.97211
05:32:30 PM	639.996	15.6249	271.95	0.44263	6.916	639.996	15.6249	352.8	0.574219	8.97211
05:32:40 PM	639.996	15.6249	349.65	0.56909	8.892	642.002	15.6739	353.85	0.575928	9.02701
05:32:50 PM	638.001	15.5762	216.3	0.35205	5.48361	639.996	15.6249	351.75	0.57251	8.94541
05:33:00 PM	638.999	15.6005	370.65	0.60327	9.41137	639.996	15.6249	351.75	0.57251	8.94541
05:33:10 PM	638.001	15.5762	304.5	0.49561	7.71965	639.996	15.6249	350.7	0.570801	8.91871
05:33:20 PM	638.001	15.5762	194.25	0.31616	4.9246	639.996	15.6249	351.75	0.57251	8.94541
05:33:30 PM	638.001	15.5762	220.5	0.35889	5.59009	639.996	15.6249	350.7	0.570801	8.91871
05:33:40 PM	639.996	15.6249	165.9	0.27002	4.21903	642.002	15.6739	350.7	0.570801	8.94665
05:33:50 PM	639.996	15.6249	204.75	0.33325	5.20703	642.002	15.6739	349.65	0.569092	8.91987
05:34:00 PM	638.999	15.6005	193.2	0.31445	4.90564	641.004	15.6495	349.65	0.569092	8.90601
05:34:10 PM	638.001	15.5762	254.1	0.41357	6.44191	639.996	15.6249	349.65	0.569092	8.892
05:34:20 PM	638.999	15.6005	226.8	0.36914	5.7588	641.004	15.6495	349.65	0.569092	8.90601
05:34:30 PM	638.001	15.5762	206.85	0.33667	5.24404	639.996	15.6249	348.6	0.567383	8.8653
05:34:40 PM	638.999	15.6005	191.1	0.31104	4.85232	641.004	15.6495	348.6	0.567383	8.87926
05:34:50 PM	638.001	15.5762	297.15	0.48364	7.53331	639.996	15.6249	348.6	0.567383	8.8653
05:35:00 PM	637.004	15.5518	208.95	0.34009	5.28899	638.999	15.6005	346.5	0.563965	8.79816
05:35:10 PM	637.004	15.5518	220.5	0.35889	5.58135	638.999	15.6005	346.5	0.563965	8.79816
05:35:20 PM	638.001	15.5762	190.05	0.30933	4.81813	638.999	15.6005	346.5	0.563965	8.79816
05:35:30 PM	638.001	15.5762	205.8	0.33496	5.21742	639.996	15.6249	347.55	0.565674	8.8386

Figure 83: Prototype 3 Testing spreadsheet data with calculations

4 Results

A partial sample of data for the first 5 and a half days is shown below:

Prototype 3 (Solar Tracking) Mean Values

Days:												
1	2	3	4	5	6	7	8	9	10	Mean	Exponentially Smoothed Mean	Area
	19.7419	19.1552	19.7808	20.3142	20.7923	20.5831	19.28	20.1711	17.6994	19.7242	18.94866952	0.0537515
	19.712	19.1255	19.7531	20.1649	20.5553	20.6129	16.4006	20.2885	17.7818	19.3772	19.02622424	0.0543075
	19.7694	19.2118	19.7531	20.105	20.4375	20.5533	16.0832	20.202	17.754	19.3188	19.06131901	0.0537444
	19.7395	19.0423	19.7808	20.1331	20.7622	20.5246	14.1521	20.1428	17.835	19.1236	19.0870668	0.0533922
	19.712	19.2118	19.7511	20.0752	20.941	20.4968	21.4189	20.144	17.754	19.945	19.09071944	0.0542619
	19.712	19.182	19.7787	19.9855	20.941	20.5246	21.0919	20.3207	17.7818	19.9242	19.17614597	0.0553739
	19.7419	19.1552	19.7214	20.0734	17.9948	20.6439	14.077	20.26	17.754	18.8246	19.25095629	0.0538179
	19.7419	19.3525	19.7214	20.0134	21.0012	20.4948	14.8399	20.2615	17.6728	19.2333	19.20832299	0.0528582
	19.7993	19.2387	19.6913	19.9836	20.7324	20.4948	11.4804	20.233	18.3121	18.8851	19.21081684	0.0529421
	19.7419	19.0155	19.6341	19.9557	19.2716	20.5256	10.653	20.2625	18.3121	18.5969	19.17824174	0.0520583
	19.7419	19.0987	19.7766	19.9259	20.1554	20.6439	14.5489	20.2921	18.259	19.1603	19.12010756	0.0524405
	19.7718	19.1552	19.8085	19.9259	20.643	20.6439	13.9934	20.3492	18.3121	19.1781	19.12412329	0.0532478
	19.7694	19.1552	19.749	19.9259	20.941	20.5841	14.1214	20.4075	18.2856	19.2154	19.12952265	0.0533244
	19.8017	19.1523	19.6616	19.8961	21.1508	20.7034	14.8928	20.4375	18.3408	19.3374	19.13811502	0.0535457
	19.8017	19.1552	19.6638	19.9557	18.048	20.6439	13.967	20.3767	18.3408	18.8836	19.15804779	0.0530848
	19.8292	19.1552	19.6341	19.9239	11.4104	20.5543	14.6283	20.2921	18.2856	18.1903	19.13060616	0.0514916
	19.7419	19.1552	19.749	19.9537	15.3062	20.5543	12.1343	20.4075	18.1485	18.3501	19.03657928	0.0507506
	19.7419	19.2118	19.6913	20.0436	21.3597	20.6728	12.7829	20.3481	18.2015	19.1171	18.96792883	0.0520377
	19.7419	19.0987	19.8042	20.1033	21.0611	20.6439	10.9077	20.6141	18.2015	18.9085	18.98284298	0.0528133
	19.7419	19.1015	19.7189	20.2494	21.1804	20.7034	10.987	20.3755	18.2015	18.9177	18.9754082	0.0525364
	20.0906	19.0719	19.6892	20.1629	21.0313	20.7034	12.5914	20.26	18.2301	19.0923	18.96963922	0.0527917
	19.7694	19.0747	19.7167	20.2229	20.8519	20.5543	12.0962	20.233	18.2545	18.9748	18.98190766	0.0528711
	19.8017	19.0747	19.7741	20.2528	20.8519	20.5543	11.1718	20.2316	17.6451	18.8175	18.98120151	0.0524894
	19.8595	19.1284	19.7741	20.3128	20.2229	20.7622	11.1454	20.3502	17.6451	18.8001	18.96483635	0.0522467
	19.7718	19.1015	19.7766	20.4023	21.0012	20.4948	12.0624	20.4375	17.6716	18.9689	18.94835932	0.0524568
	19.9492	19.1015	19.8617	20.4009	21.0012	20.4948	12.803	20.233	17.7552	19.0667	18.95040873	0.0528272
	19.7189	19.1015	19.8042	20.3128	20.9118	20.3778	14.0992	20.1724	17.754	19.1392	18.96204111	0.0530638
	19.8617	19.1043	19.7465	20.3725	19.8938	20.3778	14.0463	20.2575	17.6186	19.031	18.97975575	0.0530141

Figure 84: Prototype 3 Testing mean results

The area represents the power generated within the 10 second interval. It is calculated by adding two consecutive power values then dividing that sum by two. That fraction is then multiplied by 10/3600. This is polygonal area of the graph that is formed.

The sum of the areas will give an approximation of the power generated. The mean results were exponentially smoothed (at a ratio of 0.1 mean result : 0.9 previous smoothed value) and were then converted into an area graph:

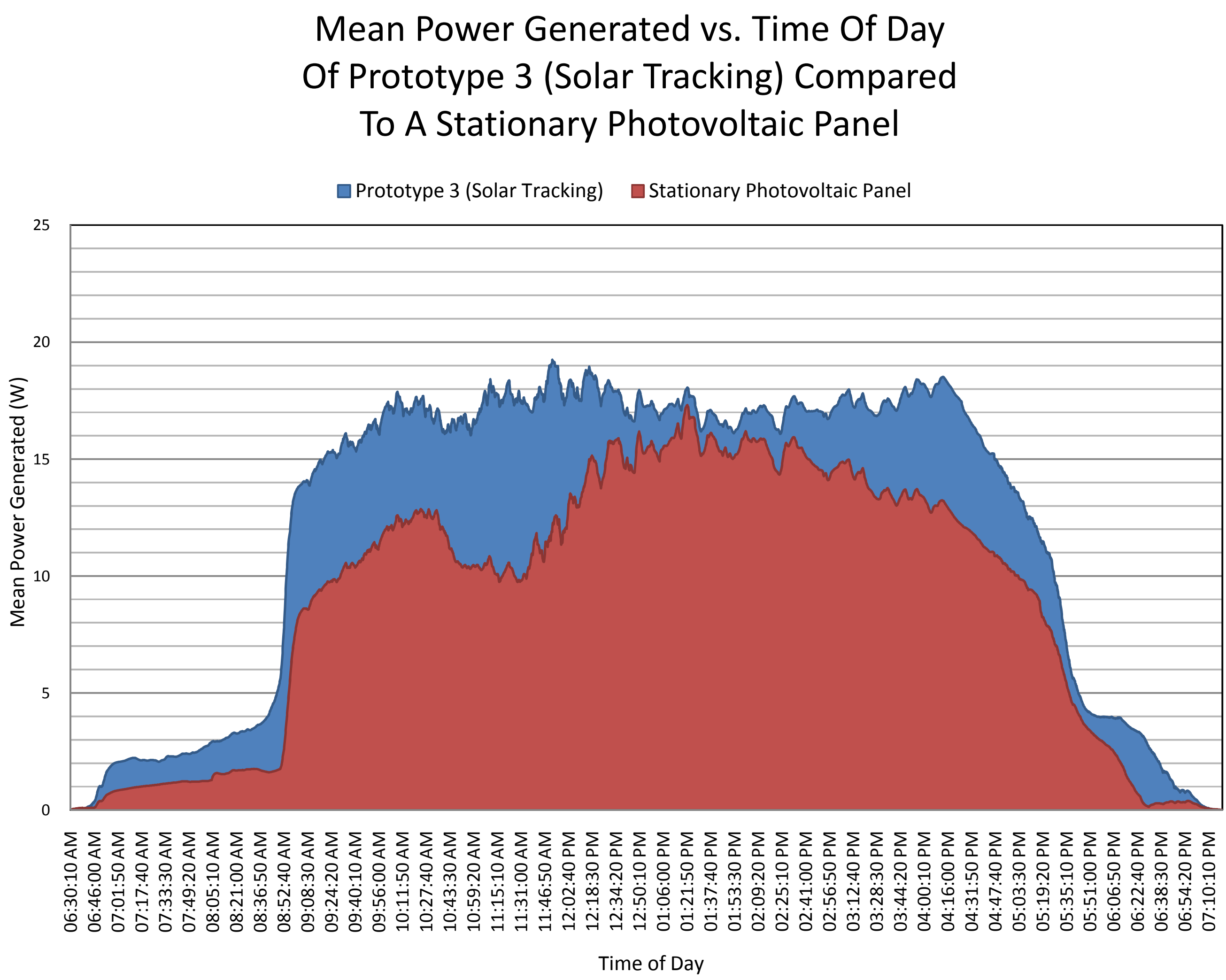


Figure 85: Prototype 3 vs. Stationary Photovoltaic panel mean power graph

The total energy generated by the prototype is approximately 154.2357 Wh and the energy generated by the stationary is approximately 114.7596 Wh. Therefore the total power generated for the prototype mean vs. the stationary mean is approximately 34.3989% or if the value is rounded off, 34.4% higher.

Through testing it was found that sun tracking capabilities improved efficiency by approximately 34.4%. This takes into account the power used by the tracking circuit. This tracking circuit uses very little power. The use is below 0.1 A at any point in time if it is not moving. When moving it can use up to 0.7 A. The panel can only move at a maximum of two seconds every one minute and 58 seconds, this can be calculated to 14 minutes per day and the maximum power that the tracking circuit can draw is 8.4 W. This is equivalent to 1.96 Wh. Spread over the course of the day, this maximum total power deficit is relatively minimal. It has been calculated into the final comparison values and the graph above.

5 Discussion

The results that were gathered reflect well on the performance of the tracking system. This justifies the use of solar tracking techniques. Prototype 3 generates a significantly greater amount of energy in comparison to a stationary photovoltaic panel.

The results were not very consistent. The lack in consistency was due to the fluctuating weather patterns. The tests were done in Cape Town. Cape Town has very unpredictable weather and this explains the roughness of the graphs. The lack in consistency is made up by the number of days worth of data. The test data covers over 9 days worth of data. This totals to 313 428 measured values of data. The sheer number of results guarantees a certain amount of reliability. If the tests were performed at a different time of year, for example winter, the results would be much smoother. This is purely due to the nature of Cape Town weather and climate.

Clear trends are illustrated by the graph:

- The mean data for prototype 3 showed a higher power value at every point over the course of a day.
- Once the sun is roughly perpendicular to the stationary panel i.e. midday, the values of prototype 3 are very similar to that of the stationary panel.
- During the mornings and evenings prototype 3 generated significantly more energy than the stationary panel. This fits the research that was done.
- The maximum power achieved by both Prototype 3 and the stationary panel are quite similar, however the maximum power is sustained by prototype 3 whereas the stationary panel only achieves maximum power for a short amount of time.
- The data seems to be fairly precise. This is in accordance with the observation that both sets of mean data peak and dip simultaneously to one another. This would indicate that the testing conditions are fair and both were tested simultaneously.

Anomalies in test data:

- In the morning both sets of data suddenly increase. The fact that the effect is simultaneous means that the comparative worth of the data is not lost, however the fact that they both suddenly increase can be explained by the location of the testing systems. They were both placed on an unobstructed rooftop, however the edge of the roof clearly has a large effect on both sets of data.
- There is a large dip in both sets of data from approximately 11:00 to 13:00. The dip is more evident in the stationary panel's set of data. This suggests that the obstruction that caused the lack in energy generation was a cloud. This would explain why prototype 3 was not affected as badly, as prototype 3 could simply adjust its orientation to face the brightest source of light, which clearly was not directly overhead. This reflects well on the performance of prototype 3.

Conclusions on test data:

- Trends on both mean power graphs follow the same, simultaneous dips and peaks. This synchronisation validates the accuracy and precision of the data results. Weather conditions would have similar favourable and unfavourable effects on both sets of data.
- The fact that prototype 3 is less effected by the temporary weather conditions indicates the superiority of prototype 3.
- The total energy generated for prototype 3 is significantly higher (34.4%) than the stationary panel. This difference in energy generation is most evident during mornings and evenings.

This prototype was a good representation of how the final product should be. The different aspects of the design worked together and the aims were met. The prototype is able to track the sun, provide power for the outputs and store the power for later use. It is also able to be transported, easily set up and stored.

This projects physical design was limited by cost and time constraints. With more money and time a smaller product could have been produced. The results gathered from this product are largely dependable. For more accuracy the product would require testing involving more results over a wider range of weather conditions.

6 Conclusions

The objective was to design and manufacture a portable power source that converts solar energy into electrical energy and can store excess energy. To minimize the size of the system, for the sake of portability, efficiency needed to be maximised.

These objectives were achieved and the rewards have been significant. Compared to a regular, stationary solar panel system, this project produces significantly more energy and is more consistent. Due to its relative high efficiency it can be much smaller than a stationary panel system and still produce similar, if not better, results. On top of all these benefits, another important factor is the portability that cannot be ignored. Also compared to a regular photovoltaic panel the prototype also provides multiple different useful outputs, as well as storage of excess energy.

7 Future Enhancements

This prototype could be improved by using stronger but lighter materials. This would help improve the portability.

Another way to improve the portability would be to create a collapsible stand. This will allow the final product to be compressed into a much thinner carry case, almost equivalent to a briefcase.

A different type of battery could be used. Lighter batteries would help to reduce strain during transport. Smaller batteries could be beneficial in two different ways. The same capacity battery could be used and the overall size of the prototype will decrease. That, or a larger capacity could be used and the overall size would remain the same.

8 List of figures

9 Bibliography

Kumar, S. 2012, Solar Tracking System, viewed 10 February 2014, <http://electronicsforu.com/electronicsforu/circuitarchives/view_article.asp?sno=745&article_type=1&id=674&tt=unhot>.

Bridgen, D. 2012, 555 Timer, viewed 10 February 2014, <http://www.davidbridgen.com/555.htm>.

Eleccircuit. 2012, Microprocessor dc regulator supply 5V 3A by LM323K, viewed 12 February 2014, <http://www.eleccircuit.com/microprocessor-dc-regulator-supply-5v-3a-by-lm323k/>.

Author unknown. 2007, Power.gif, viewed 31 March 2014, <http://forum.tlienhard.com/ts1000/home.comcast.net/~sb6811/ts1500/power.gif>.

Micro Robotics. 2014, 7812circuit, viewed 29 April 2014, <https://www.robotics.org.za/new_images/7812_circuit.jpg>.

Author unknown. 2013, Mantech products, viewed 29 April 2014, <http://www.mantech.co.za/stock.aspx>.

Multiple authors. 2014, Gyroscope, viewed 30 April 2014, <http://en.wikipedia.org/wiki/Gyroscope>.
Gregory. 2010, Convert Decimal Hours to Time in Exel, viewed 27 February 2014, <http://excelsemipro.com/2010/10/convert-decimal-hours-to-time-in-excel/>.
Multiple authors. 2014, Electric power, viewed 16 March 2014, <http://en.wikipedia.org/wiki/Electric_power>.

R S Components. 1999, 2N3055 Specs, viewed 3 May 2014, <http://za.rs-online.com/web/p/products/4864476/?cm_mmc=ZA-PPC-0914-_-google-_-3_Supplier_M-Z_02_2012-_-67d5e38c-cd63-96a9-ca3d-000040c70855>.

STMicroelectronics. 2014, L8700 Datasheet, viewed 3 May 2014, <http://www.alldatasheet.com/datasheet-pdf/pdf/22614/STMICROELECTRONICS/L7800.html>.

AllDataSheet.com. 2014, ATMEGA168PV Datasheet, viewed 3 May 2014, <http://www.alldatasheet.com/view.jsp?Searchword=ATMEGA168PV>.

AllDataSheet.com. 2014, TIP35A-D Datasheet, viewed 3 May 2014, <http://www.alldatasheet.com/view.jsp?Searchword=TIP35A-D>.

Arduino. 2014, Arduino - ArduinoBoardUno, viewed 3 May 2014, <http://www.arduino.cc/en/Main/ArduinoBoardUno>.

AllDataSheet.com. 2014, PB137 Datasheet, viewed 3 May 2014, <http://www.alldatasheet.com/view.jsp?Searchword=PB137>.

NASA. 2011, How do Photovoltaics Work?, viewed 22 June 2014, <http://science.nasa.gov/science-news/science-at-nasa/2002/solarcells/>.