

Automated salt watcher

Developing an open-source measuring system that can automatically measure the soil resistance of all possible 4-electrode combinations



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Thesis Report

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Thesis Project

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Abstract

Waterschap Scheldestromen is carrying out a particularly innovative project named Multiflexmeter (MFM), of which the objective is to look for ways to measure the water level digitally. This means some properties and characteristics of water needs to be researched on, such as the salinity and the corresponding conductivity. At the request of Waterschap Scheldestromen and Province of Zeeland, in the Netherlands, an automated soil resistance meter (watcher) with switchable electrode set is required to be designed based on previous related research. The working principle of an existing commercial handheld measuring device (Chauvin Arnoux C.A 6460) is regarded as the designing reference. The aim of this project is to develop an open-source measuring system that can automatically measure the resistance of all possible 4-electrode combinations using Wenner method.

The entire project moved forward under the guide of V-model method. The V-model was not applied in this project rigidly, instead, several flexible adjustments had been implemented in order to reasonably adapt this methodology to the actual condition of this project. Following the V-model, the design phase was divided into system design, sub-system design and component design. In addition, main question and sub-questions were raised appropriately.

The core part of the ultimate product of this project is mainly one Printed Circuit Board with 23 optocouplers and a measuring chip on it. Besides that, there are Arduino microcontroller and signal generation circuit externally. The cost of designing, purchasing components and assembly is under 100€, which is within the budget. This system prototype fulfills the task of switching automatically and measuring accurately (errors under 6%) in lab conditions by using 25 ideal resistors to test whilst the system did not fully achieve the expected performance in the field test. The on-site test results were fairly unstable and it was noted that with the test continuing, the accuracy and stability of the system were declining gradually.

There are some possible reasons causing the different performance of this same system under the in-lab conditions and on-site conditions respectively. The corresponding discussion of this part is in Chapter 5 and Chapter 6.

On the whole, further research related to this project is required to find out the exact reasons that lead to poor performance of the system prototype in the field test and the corresponding solutions. Additionally, there is still much room for improvement the system designed in this project. For instance, considering adding intermediate relays is one of the possibilities to optimize it. Also, there will be opportunity for this system to be integrated into the huge-scale Multiflexmeter project system in the future.

Foreword

As an Engineering-Mechatronics student from HZ University of Applied Sciences, I accepted this thesis project provided by the company Waterschap Scheldestromen. This internship lasts about 4 months and it is coming to an end now. The project I carried out is called “Automated Salt Watcher”, during which there are plenty of chances for me to put the theory knowledge I have learned before into practice. Definitely, it is unavoidable that I have met several problems and barriers during the past few months but thankfully, I addressed those challenges and finally grew through them. This valuable experience would influence me significantly in my future work and studies.

Along the way, it was full of hardships, but I also derived a lot of help. I would like to sincerely thank my supervisors from HZ University of Applied Sciences: Mr. Willem Haak and Mr. Bert Verhage. Their feedback, suggestion and instruction are greatly helpful for my project, especially for my thesis. I also would like to show gratitude to my in-company mentor Mr. Jos Goossen. His help was always timely and usable, greatly contributing to the completion of my thesis project. Besides, my company colleague Mick van Eerd, Lennart Murk and Haobo Guo deserve my thank-you as well. They gave me encouragement and many tips when I was trapped. Finally, I indeed appreciate my parents’ support to me. There were few moments I was in dilemma and almost wanted to give up, it was them who gave me the warmth and strength, which made me struggle to bounce back and complete the project in the end. From my point of view, I could not finish this project and thesis without their spiritual support and help.

Xuesong Zhang

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Abbreviations

A	Ampere
AC	Alternating current
ADC	Analog-to-digital converter
C.A	Chauvine Amoux
DC	Direct current
EC	Electrical Conductivity
I	Current
V/U	Voltage
RMS	Root mean square
Vrms	Root mean square of Voltage
LED	Light-emitting diode
VCC	Volt Current Condenser
GND	Ground
SCL	Serial clock line
SDA	Serial data line
SSR	Solid state relay
SMD	Surface mounted device
THD	Through hole device
mS	Milli siemens
PCB	Printed circuit board
°C	Celsius
USB	Universal serial bus
A0/A1/A2/A3/AIN0/AIN1/AIN2/AIN3	Analog input port
Ω	Ohm
€	Euro(s)

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Chapter 1: Introduction

In former part of this chapter, the background information of the company, assignment and the analysis of the assignment will be described. In the latter part of this section, the objectives/deliverables, research questions (main question and sub-questions) and project boundaries will be displayed.

1.1 Background information

In this sub-chapter, company background which includes the specialties of company, company size and so on, will be introduced firstly. The graduation assignment background will also be simply presented, and further information of the assignment is in next sub-chapter.

1.1.1 Company background

Waterschap Scheldestromen is a company that has responsibilities for strong dikes, safe country roads, clean surface water and the right amount of water in the ditch in the area of Zeeland (Waterschap Scheldestromen, 2021). Waterschap Scheldestromen is not a large international company, but it does not mean lack of freedom and flexibility when working here. Also, working conditions and atmosphere are friendly and all staff here are attached importance to.

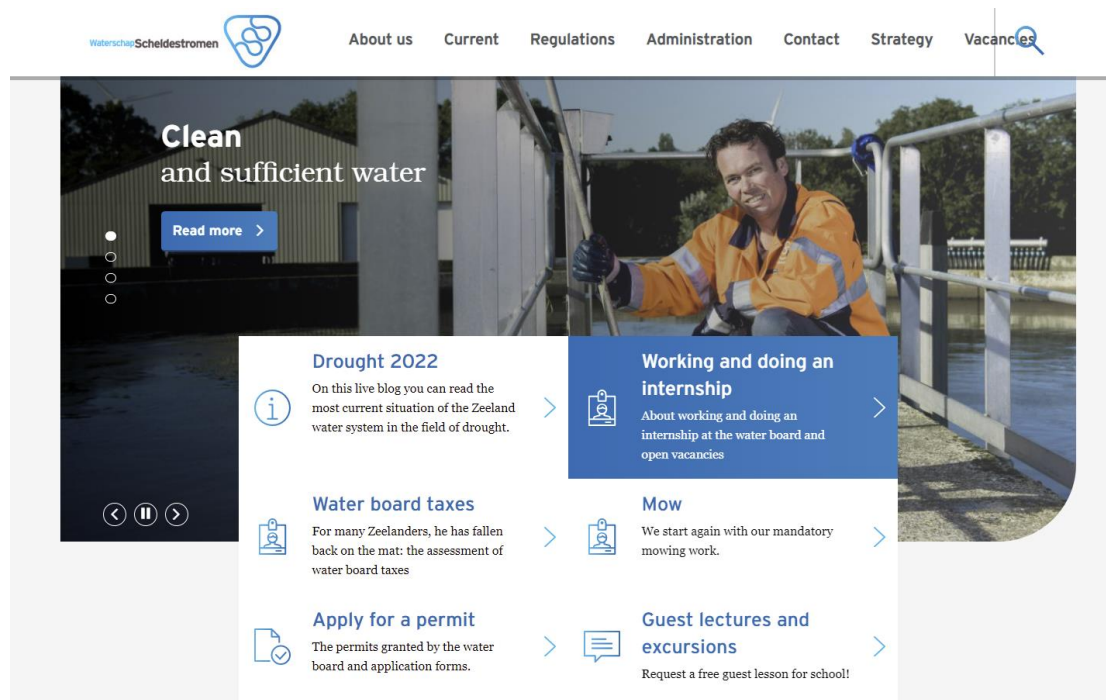


Figure 1 Official website of Waterschap Scheldestromen

Every four years there are water board elections. After that, the new board determines the ambitions and starting points for the four years that it has been elected. This concerns, for example, water safety, clean water, sustainability and the maximum increase in taxes. This is laid down in the water board's strategy paper and is the basis for all other plans and policy documents.

Waterschap Scheldestromen carries out several important projects in various areas such as flood defenses, water management, road management, etc. In each field, there are also some sub-project or activities which satisfy many kinds of the conditions in Zeeland.

Among those projects, there is one project corresponding to this internship assignment mostly. These years Waterschap Scheldestromen has been carrying out a project—Multiflexmeter, which

aims at providing cheap, energy-saving solution for monitoring water systems such as water level or salt concentration with the internet of thing (IOT). The most two attractive properties of this project are—a. completely open source. b. developed together with students, volunteers and companies. At the end of 2017, Multiflexmeter won the Water Innovation Prize.

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1.1.2 Assignment background

With climate changing in the Netherlands, there is less and less rainfall during the summer. Therefore, the underground soil obtains insufficient fresh rainwater to maintain balance in the salt concentration, with the impact of groundwater extraction, all of which lead the threat of salinization of the shallow groundwater. As a result, the role of water quality monitoring of fresh groundwater is becoming quite more important than before. The picture below displays the groundwater distribution condition in Zeeland.

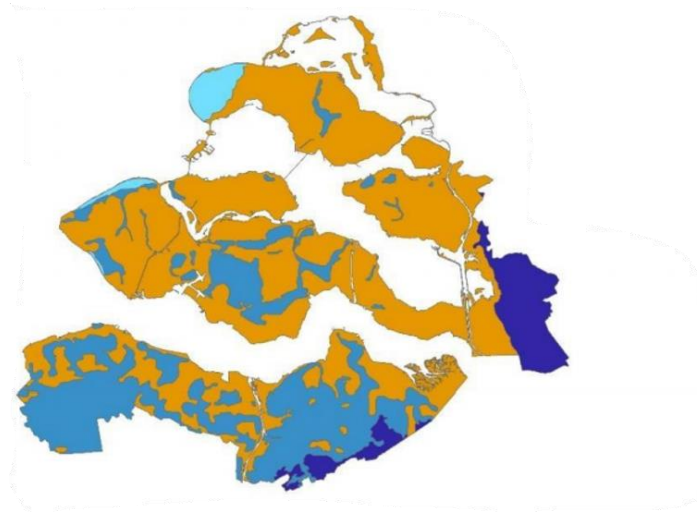


Figure 2 Groundwater distribution in Zeeland, colors represent different areas (Pauw, 2020)

In order to avoid salinization to the greatest degree, it is necessary to know the underground salt concentration of soil in detail. There is relevant research that has been carried out in 2021 by former students into two aspects-- construction of a measuring instrument and a system for automatic switching between electrodes.

In 2021, student Pinqi Guo was responsible for the thesis project which was aiming at designing 4-electrodes soil resistance meter. In the end of his project, he found two main problems: The first

problem is the existing signal generation subsystem cannot be combined with the salt watcher prototype. The second problem is the values measured by the existing model is not precise enough. Student Yuyao Tian carried out another thesis project which was aiming at designing an automatic electrode switch system of salt watcher. He chose to use the “bungalow” design, which is a switch system with logic control circuit and a flat layer of SPST-NO switches. Due to time limitation, finally the prototype of his project only contains 8 electrodes but it had proved the concept of his design. Their designs need improvement and in addition, the useful outcomes of these two projects have not been combined yet.

In 2022, there is possibility of combining the separate outcomes of two previous projects and make them integrated to design a complete automated electrode switch salt monitoring/measuring system based on Wenner method which gave the birth of the thesis project for 2022.

1.2 Assignment description

The basic measuring principal is within the same type of soil, the distribution of salt can influence the specific electrical resistance. So far, there is a handheld measuring device (Chauvine Amoux C. A 6460) designed for ground resistance using the Wenner method. There are four terminals to be connected and an LED screen for displaying data of this instrument. Normally, more manpower and material resources are needed on account of manual operation of this old kind measurement instrument. To summarize, the traditional measuring process is based on manual measurement for each 4-electrode set, using a handheld device C. A 6460 which is also called earth resistivity tester.

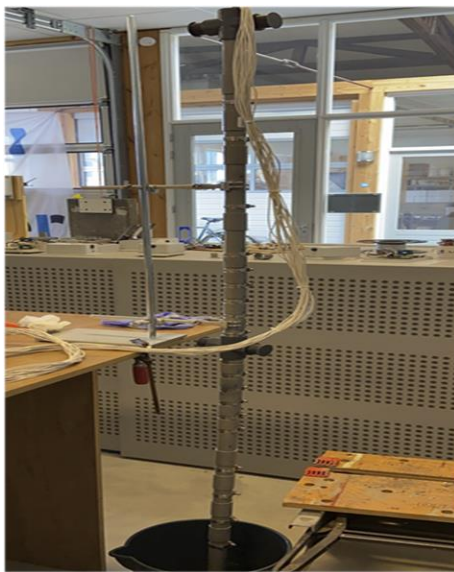


Figure 3 Prototype salt watcher cable (shot in the Dockwise laboratory)

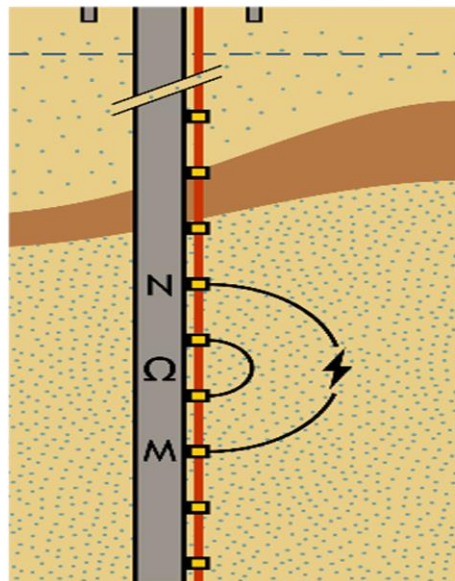


Figure 4 Wenner method (Goossen, 2021)

These years, a test set-up has been built at HZ-Sea-Lab (as shown in Figure 5 below) for testing the prototype of the salt watcher cable. The main objective of this test is manually carrying out resistance measurements which were set at different salt concentrations and salt/fresh interface. When scaling up this experimental setup, Waterschap Scheldestromen wants the measurements to take place automatically, with the measurement data becoming available via IoT.

As mentioned earlier, two former students have implemented some research about this purpose last year (2021 thesis projects). Pinqi Guo was responsible for elaborating on the proof of concept and making a measuring meter prototype based on the measuring method (Wenner method). Yuyao Tian

was responsible for the automatic switching of the electrode sets. Due to that these two projects were carried out separately, the combination between them was left almost blank. But in real measurement situation, usually both of them need to be implemented, and sometimes, cooperation of them is necessary.



Figure 5 Experimental setup at HZ SEA Lab

On the basis of previous research and the requirement of this project, the problem of designing an automated salt watcher system is composed of 3 main parts: automatic switch subsystem design, measuring subsystem design and the interaction between these two subsystems. The past research results can be reference design ideas for both subsystems. However, scheme of realizing the interactive function between these two systems still remains unknown.

In terms of that the design reference of Pinqi's design is the measurement system in the resistivity tester C.A 6460, it is still requested from the client that the measurement part in this project refers to the measurement principle and process of the tester C.A 6460. In other words, the measurement system should simulate the working principle of that instrument C.A 6460 as much as possible. Mick van Eerd, one colleague at Waterschap, pointed out some properties of C.A 6460 in one report after testing on it, as shown below. These properties observed will be the design reference in this project.

Observations from the test:

1. The device measures resistance using (discrete) 10mA, 1 mA or 0,1 mA.
2. The device has an accuracy of <1% in lab conditions with fixed resistor testing.
3. The output power is ranging 70 mW to 650 mW.
4. Frequency is not very stable measured by the oscilloscope. Frequency values range from 400 to 3600 Hz. Most (stable) readings were performed at a frequency of ~800 Hz.
5. Output measurement voltage is low, <600 mV.

Figure 6 Excerpt from Mick's report (Eerd, 2021)

As for the structure of the system to design, all known until now is the expected complete system necessarily contains automatic switch subsystem, measuring subsystem and functional collaboration between subsystems. Both these two subsystems need external power but it is required to supply the measuring system with AC square wave signal source to avoid the influence of polarization among the electrodes. There are 26 terminals which are connected the electrodes underground one by one. The final salt watcher system should have the capability to connect 26 terminals and switch

among those in a specific order controlled by code. Connection between 4 terminals chosen and the measuring system exists and then the resistance between electrodes would be measured and displayed. Based on the Wenner method theory, 4 electrodes are chosen to measure at one time so there are 4 wires between measuring system and switch system. Finally, the digital signal containing the measurement data would be transferred to data display system but this step is not necessary. Another option is to display the values directly in the software monitoring window.

Figure 7 below illustrates the expected system structure based on the problem analysis.

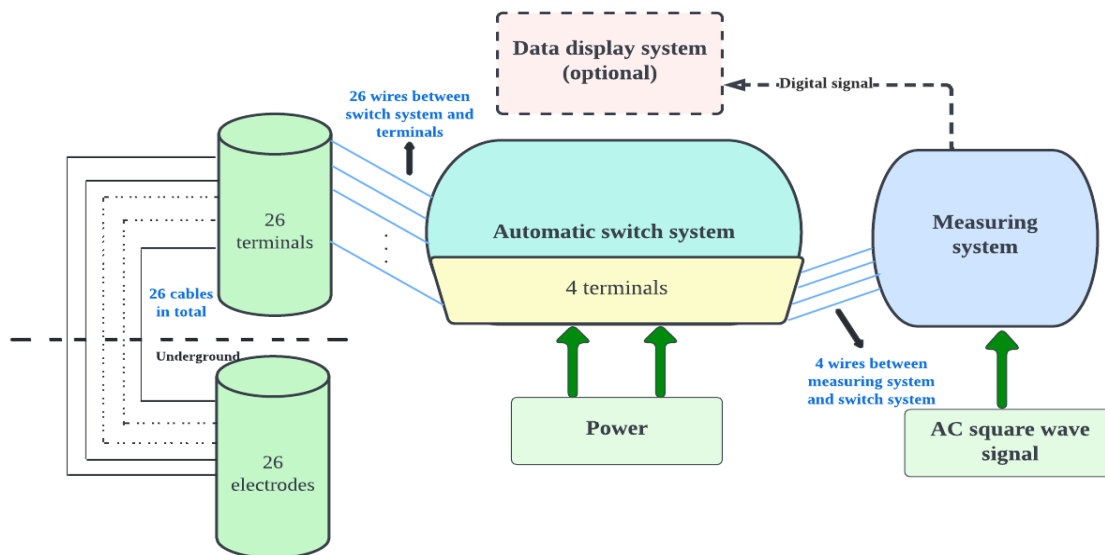


Figure 7 Expected structure of the automated salt watcher based on the problem analysis

In conclusion, the main assignment of the 2022 thesis project is to delve into both sub-projects, optimize them and eventually combine the useful outcomes of two previous projects, developing an open-source measuring system that can automatically measure all possible 4 (Wenner) electrode combinations.

1.3 Objective & Deliverables

Objectives and deliverables for a thesis project are quite significant matters that deserve attention. In general, research objectives describe what we expect to achieve by a project. Deliverables are the items which need to be submitted at the end of this graduation project.

1.3.1 Objectives

The objective of this research is to integrate existing research results and finally build a prototype which has the capability to measure the soil resistance underground on the basis of two previous relative projects. Specifically speaking, the system applied in the prototype uses 4-electrode Wenner method as measuring theory and can switch between electrodes automatically. Besides, realizing the educational goal of graduation project is also one objective of this research.

1.3.2 Deliverables

- 1) The design of the whole measuring system
- 2) System & sub-system & component design
- 3) System prototype

- 4) Prototype description
- 5) Test plans and corresponding report of test results
- 6) Final thesis report

1.4 Research questions

The research questions are divided into one main question and 6 sub-questions that relates to research method.

1.4.1 Main question

What is the design of an open-source measuring system that can measure the electrical resistance of underground soil using the principle of Wenner method, with several sets of automatically switching 4-electrode (less than 26 electrodes in total) combinations?

1.4.2 Sub-questions

Orientation phase (3 weeks):

- 1) What is the principle and operation progress of the existing measurement method using the traditional salt watcher device (Chauvin Arnoux CA 6460)?

System design (8 days) & sub-system design (6 days) phases:

- 2) What are the descriptions of the entire system and sub-systems?

Component design phase (8 days):

- 3) What are the necessary components and their corresponding test plans of this open-source measuring system?

Component integration phase (1 week) & Sub-system integration phase (10 days):

- 4) What are the test results and actual function of each sub-system and do they accord with the expected design and expected results?

System integration phase (2 months):

- 5) What are the test results of the final integrated measuring system?
- 6) What is the corresponding analysis of those final test results?

1.5 Project boundaries

- 1) This project is not supposed to start from scratch (based on previous projects).
- 2) Basis is a commercial instrument with 4 electrodes can be measured.
- 3) Use Wenner method (4-electrode measuring principle).
- 4) First solve the switch problem of sequential shortest equidistance switch. If test for that is successful, move to consider other switch possibilities.
- 5) There is no need in this project to continue completing both previous sub-projects.
- 6) The design of the sensor cable is not in the scope of this project.

Chapter 2: Theoretical framework

This chapter will give detailed demonstration of relevant knowledge, theory and research required for this project. The search plan for this project can be found in [Appendix I](#). To realize the desirable result of this project, the items listed in the search plan are necessary to research in order to guarantee the outcomes of the project.

2.1 Measuring system of previous project

One of the reference systems is the measuring system designed and tested by one former student, Pinqi Guo, and the system prototype is shown below. Pinqi chose one analog-to-digital converter (ADC) ADS1115 as the voltage sensor and one amplifier AD8210 as the current detector.

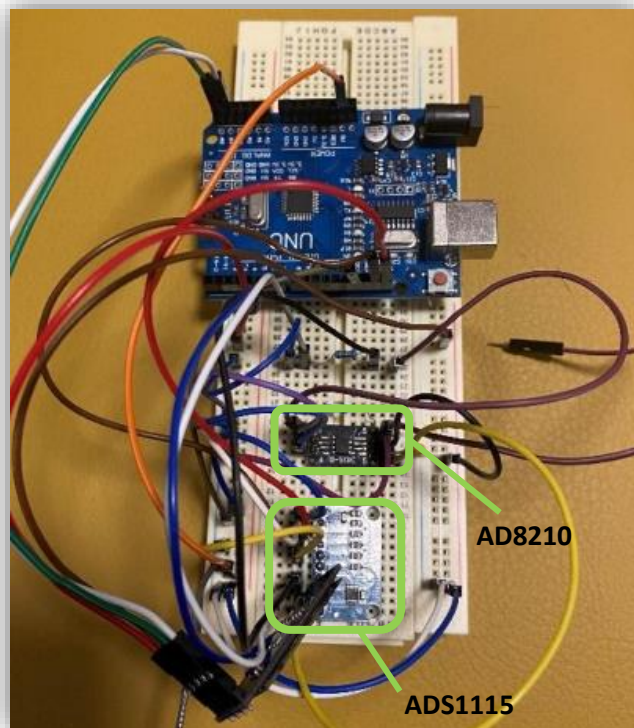


Figure 8 System prototype designed by Pinqi Guo (Guo, 2021)

is possible to use ADS1115 to detect the current I equivalently. The formula is displayed below:

$$\text{The current } I = \frac{U}{R}$$

Where:

U: Voltage drop of the reference resistor;

R: Resistance of the reference resistor

After testing, the accuracy of ADS1115 to measuring the voltage of component in the circuit had been proved that and the errors were lower than around 8%. However, the accuracy of AD8210 did not meet the design requirement, of which the error range is 20.7%-39%.

Therefore, ADC ADS1115 will continue to be used to measure voltage in this project. The details of ADS1115 can be found in [Appendix VIII: Schematics and properties of core components](#). The component AD8210 will be discarded and new current sensor will be determined and designed.

It is noteworthy that there are 4 input channels of ADS1115 and the input type can be differential or single-ended (shown in Figure 9). This means with the assistance of a reference resistor, it

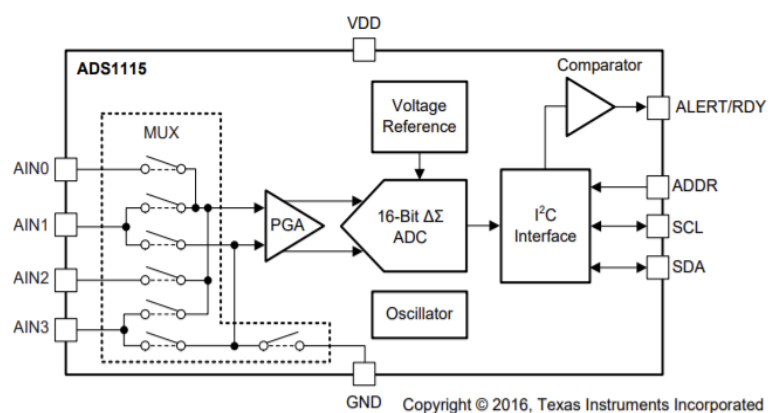
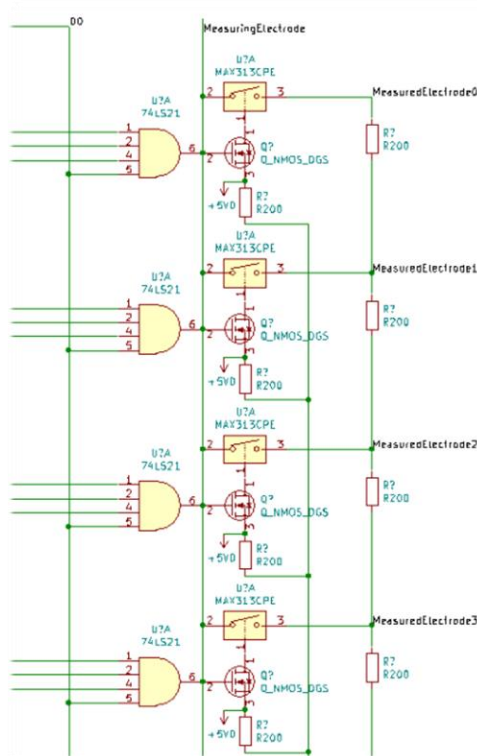


Figure 9 ADS1115 block diagram (ADS1115 Datasheet, 2018)

2.2 Switch system of previous project

The automatic switch system of electrodes, in charge of former student Yuyao Tian last year, applied the bungalow design, as Figure 10 shows.



In the bungalow design, SPST switches were used, of which the specific type is analog switch MAX313CPE. In Yuyao's final prototype, 8 electrodes instead of 26 electrodes were connected to the measuring terminals and the ultimate test results can be regarded as the proof of concept for this design.

The whole switch circuit will contain $26 \times 4 = 104$ SPST switches and $5 \times 4 = 20$ control signals (Tian, 2021). The price of MAX313CPE at online shop was more than 10€ for each (as shown in Figure 11). In this case, if continue to design using MAX313CPE for the entire switch system, there will cost a lot.

Therefore, the previous switch system is determined to be discarded and new switch circuit will be designed according to the requirements. Other switch circuit design will be researched and decided for the final switch system design of this project.

Figure 10 Partial schematics of the designed switch system (Tian, 2021)

<input type="checkbox"/>	MAX313 CPE+	2518640	Analogue Switch, 4 Channels, SPST, 10 ohm, 4.5V to 30V, \pm 4.5V to \pm 20V, DIP, 16 Pins		47 Op voorraad	Each	1+ € 15,66 10+ € 14,39 25+ € 13,79 50+ € 12,97 100+ € 12,15	1 Min: 1 Mult: 1	SPST
			MAXIM INTEGRATED / ANALOG DEVICES						

Figure 11 The price of MAX313CPE from Farnell (Farnell Store, 2022)

2.3 Switch selection

In terms of the high-cost and wiring complexity and so on, previous switch system will not continue to use. According to the requirement from client, the switch must be automatically operated, which means manual switches are not in consideration for this project. As for the selection of switch, the first thing is to determine the type of switch: contact or contactless (non-contact) switch. After research, the characteristics of contact switch and contactless switch are listed below.

Table 1 Comparison between contact switch and contactless switch

Switch Type	Power Dissipation	Response Time	Switching Arc	Lifespan	Reliability
Contact Switch	High	Slow	Yes	Short	Medium
Contactless Switch	Low	Fast	No	Long	High

It is manifest that compared with contact switch, contactless switch boasts more merits. After comprehensive consideration, contactless switch is chosen to be applied in the switch sub-system

design in this project. In this section, some contactless switches in the market are researched and compared. The comparison table containing the characteristics and application of some switches is in the [Appendix II](#).

2.4 Soil condition

Due to the fact that original aim of designing a type of automated salt watcher is to measure the conductivity/resistivity of soil which represents the soil salinity, soil condition is an issue that requires to research about. In summary, the soil condition related to this project is soil salinization and soil conductivity. The detailed information can be found in [Appendix III: Soil condition \(Salinization & Conductivity\)](#).

2.5 Measuring method & device

In this section, Wenner method which is the measuring method used in this project will be demonstrated including figure and formula. After brief introduction of measuring method, the properties and functions of specific commercial measuring device Chauvin-Arnoux-6460 will also be displayed. The reason why researching about this device is according to one of requirements of this project, this specific measuring device plays a role as reference.

2.5.1 Wenner method

Soil resistivity measurement mainly includes soil sample method, two-point method, three-point method (three-point method) and four-point method (four-point method). The four-point method is easy to operate and generally adopts the four-point method. Quadrupole method can be divided into equidistant method (or Wenner method) and non-equidistant method (or Schlumberger method). In practical work, the Wenner method is usually used to measure the soil resistivity at the location of the project. The small electrode is buried in four small holes arranged in a line in the measured soil. The buried depth is defined as “b” and the straight-line interval is defined as “a”. The test current I flows into the outer two electrodes, and the potential difference V between the inner two electrodes can be measured with a potential difference meter or a high resistance voltmeter. V / I is the resistance R expressed in redundancy.

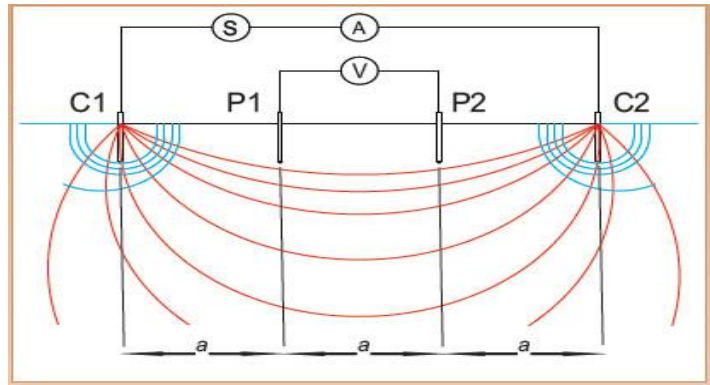


Figure 12 Wenner Four Point method (Soil Resistivity Testing -- SUMO Services, 2020)

If a is the distance between two adjacent electrodes, the resistivity ρ expressed in units of a and b is:

$$\rho = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}}$$

Where: ρ : resistivity of original soil [$\Omega \cdot m$]; R : original measured resistance [Ω]; a : distance between adjacent electrodes [m]; b : electrode buried depth [m]

Additionally, when the test electrode penetration depth (b) is less than 0.2a, factor b can be regarded to equal to zero, then the formula can be simplified to:

$$\rho = 2\pi a R$$

2.5.2 Measuring device

The Chauvin-Arnoux-C. A-6460 is one ohmmeter equipped with digital displays for earth and resistivity measurements in the field. It is particularly well-adapted to use in difficult conditions, in the presence of interference voltages, high earth currents or highly resistive auxiliary connections. (C.A 6460 & C.A 6462 User's manual, 2018). The detailed introduction of C.A 6460 can be found in [Appendix IV: Introduction of Chauvin-Arnoux-C. A-6460](#).

2.6 Practical testing/experimental issues

The HZ sealab is built for realizing the practical testing for several projects. When implementing the practical measuring test or experiments, there are many issues that deserve attention. Additionally, the practice part in this project needs the experimenter has sufficient basic practical skills which supports the smooth implementation of the whole test.

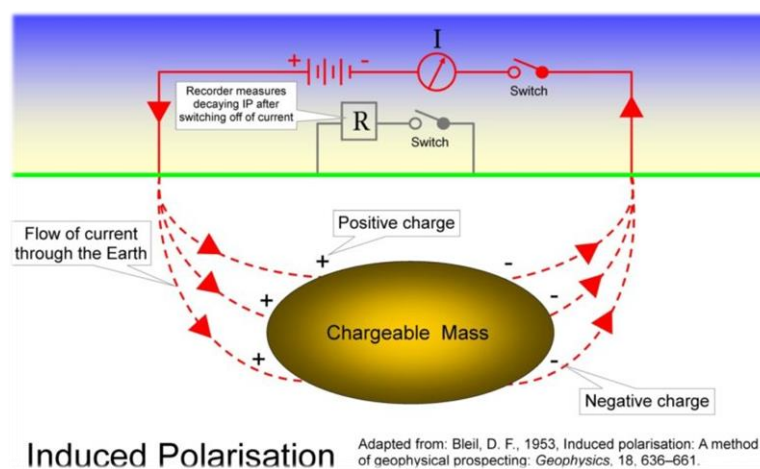


Figure 13 Inducement of polarization (Tilley, 2013)

Under the action of external electric field, there will be electrochemical interaction between metal electrode and soil, which destroys the original galvanic layer and forms a galvanic layer with new potential, that is, electrode polarization effect. The polarization potential will be generated on the electrode surface, and there is a polarization potential difference between the measuring electrodes P1 and P1, which interferes with the

measurement accuracy. For wet soil with high salt content, the polarization effect of electrode is obvious, which seriously interferes with the measurement results. Therefore, copper electrode, anti-polarization electrode or AC power supply should be used to eliminate the influence of polarization effect to great degrees.

When using Wenner method to measure soil resistivity, the four electrodes shall be in a straight line, and the resistivity calculated by this kind of symmetrical quadrupole resistivity calculation is accurate. When the four electrodes are not on a straight line, there is an error in the calculation result. Therefore, the general specification stipulates that the deviation of the actual placement direction of the electrode from the predetermined direction should be less than 5 degrees.

Due to that this project is on the basis of handheld instrument C.A. 6460, it is also necessary to learn the datasheet of this device and master the usage method of it. The test results of this device can be regarded as desirable(accurate) reference values to compare with the values measured by the system designed in this project.

The results, if adequate investigation is not made prior to the test, or the test is not correctly undertaken, may be incorrect or misleading. To overcome these problems, the following data gathering and testing standards are recommended (Carelabz, 2021):

- In the initial research stage, it is necessary to provide sufficient background, determine the test plan on this basis, and then explain it according to the test results.

- The accuracy of the results can be determined by matching the new rainfall data with the seasonal average, minimum and maximum values of the location.
- When selecting the test type, it is necessary to consider the factors of the test method, such as the maximum probe depth, the required cable length, the efficiency of the measurement technology, the cost and the ease of data interpretation.

Some practical testing recommendations:

- Eliminate mutual coupling or interference due to leads parallel to power lines.
- Make sure that the instrument, devices and set up is adequate
- Set up the correspondent criteria and check for accuracy
- Decrease contact resistance to a great degree
- Instruct staff to use finer test spacing in areas showing sharp changes
- After finishing tests, plot test results instantly so as to identify specific problem areas



Also, it can be seen from the Figure 14 that the saltwatcher tank is more than 2 meters high which leads danger and inconvenience to operate on it especially the weather condition is under expectation, for instance, there is storm or even strong wind that day. Therefore, the experimenter is always supposed to pay attention to personal safety to avoid any accidents.

Figure 14 Saltwatcher set-up tank at HZ SEA Lab

2.7 Arduino Microcontroller

To realize the automatic switching of electrodes, microcontroller board is necessary. There are several types of Arduino boards designed to meet different use requirements. In this project, mainly two types of Arduino board are considered to use: Arduino Uno and Arduino Mega. The core

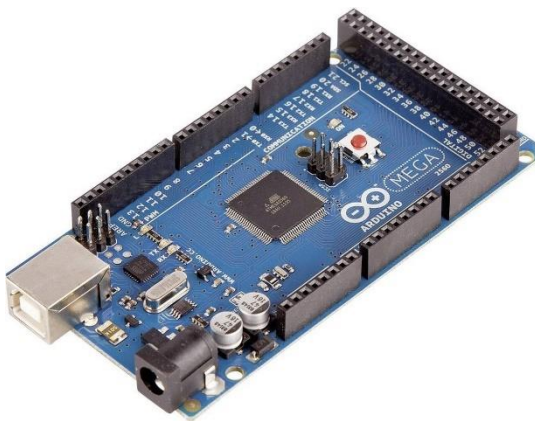


Figure 15 Arduino Mega2560 (ArduinoStore, 2021)

processor of Arduino Uno is ATmega328p. It has 14 digital input / output pins (6 of which can be used as PWM output), 6 analog inputs, 16mhz crystal oscillator clock, USB connection, power jack, ICSP connector and reset button. Just connect the computer through USB data cable to power supply, program download and data communication. In terms of the existence of switch sub-system, there will be more than 20 digital pins needed from Arduino board, which is because those pins are used to control the switches that relate to 26 electrodes. Therefore, Arduino Uno board probably cannot meet the requirement. In this case, Arduino Mega required. Arduino Mega is a development board based on ATmega2560. It is designed for more complex Arduino development projects. It has 54 digital input / output pins (15 of which can be used for PWM output), 16 analog output pins, 4 USART hardware serial interfaces, 16 MHz crystal oscillator, 1 USB interface and 1 power interface. It supports online serial programming and reset keys. The final choice of Arduino board depends on the real condition. The technical details of each Arduino Board can be found in [Appendix V : Comparison between Arduino Uno & Arduino Mega 2560](#).

2.8 Price & Cost

Cost of a project includes several items like the price of components, PCB price and assembling labor cost and so on, varying depending on the type and work quantity of project. The expenses in the project deserve attention and considered on account that the project cost is also one significant issue for project management.

2.8.1 PCB price

The type and complexity of PCB vary on the basis of different project objectives. Therefore, when manufacturing a PCB, the expense influence by many factors is various greatly. The main two types of PCB are Through-Hole Mounting (THM) and Surface Mount Technology (shown in the figures). What is more, it is also required to take into account that both human labor cost and machine cost, finding out balanced plans for building the system prototype. The details of information of PCB price are in [Appendix VI](#).



Figure 17 Surface Mount Technology PCB (DigiSource, 2021)

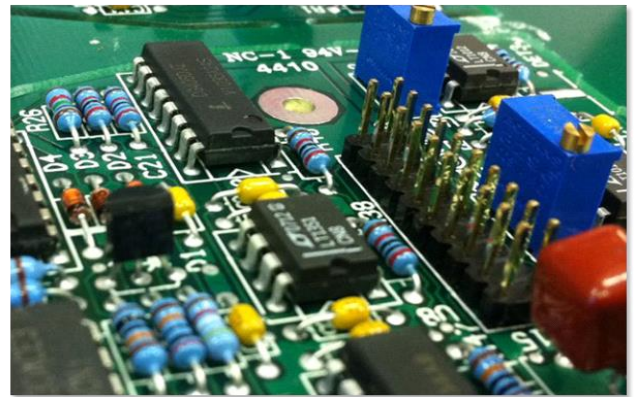


Figure 16 Through-hole Technology PCB (DigiSource, 2021)

2.8.2 Housing price

For this project, housing of the prototype is not necessary after the discussion with in-company mentor. But it is also possible to consider the cost of housing.

The most feasible and convenient method is to design and build the housing model using Solidworks (a 3D CAD design software) and then print it by 3D printer at HZ. Besides the cost of software, the only spend is on materials for 3D printer, which is about 5-10 euros.

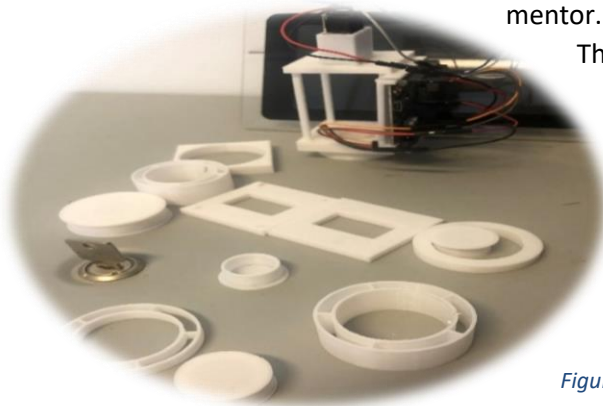


Figure 18 Some components printed of housing

2.8.3 Labor cost

As for projects, especially mass products produce is required, labor cost cannot be neglected. The human labor cost differs significantly because the development level of different regions in the world is different. The Netherlands is a developed country and a member of the European Union (EU), therefore, it is meaningful and valuable to compare the human labor cost in the Netherlands and that in the whole EU. In addition, reducing labor cost as much as possible is also important in a project management. All details are in [Appendix VII: Labor issue](#).

Chapter 3: Methods

In this chapter, V-model method, the project management (design) method chosen for this project, will be introduced firstly. After that, the reason why applies V-model to this project and the corresponding method application will also be illustrated. In the end of this section, the specific activities and deliverables during each project phase will be displayed.

3.1 V-model method

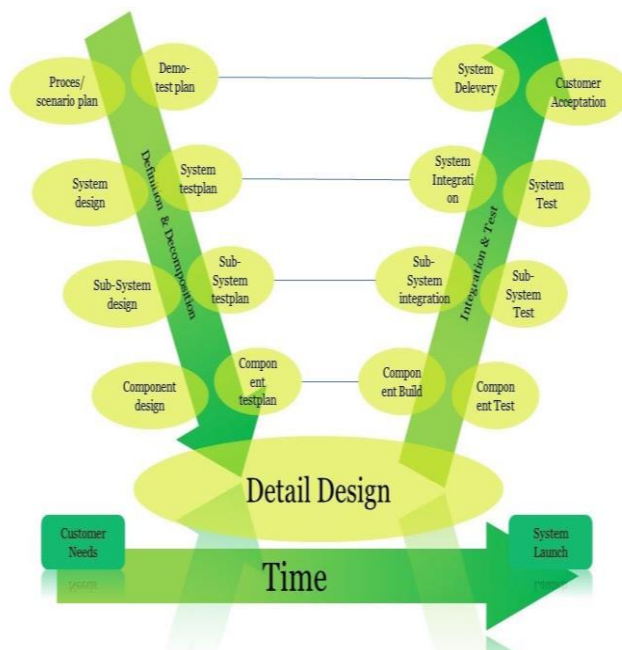


Figure 19 V-model method (Kwekkeboom, 2019)

The V-model consists of two main stages. Design and integration. V-model includes low-level test (unit test) and high-level test (system test). Equally important, V-model can clearly show the various stages of development and testing. V-model is also improved gradually from top to bottom. There is a clear division of labor in each stage, which is conducive to the control of the whole project. The V-model is iterative and allows users to move back and forth between each sub phase (Kwekkeboom, 2019). Following the structure of V-model and through iterative verification and confirmation, this method can ensure that the final design system release meets the customer's requirements.

3.2 Reason for applying V-model method

In V-model method, each step of the development cycle has its related testing phase and this is the main reason why V-model is appropriate to apply in this project. The emphasis of V-model method is functionality accomplishment, of which the aim is to develop a working prototype by dividing up the system and conducting multiple tests.

The objective of this project is to design a hardware prototype which boasts some specific functions. The system in the prototype consists of several sub-systems and for each sub-system, there are corresponding components do design. V-model can efficiently guide the division of both the system and sub-system, making the final system designed more reasonable and reliable.

What is known that the realization of the system function needs the help of tests, called verification or validation. According to V-model, the relationship between designing and testing is underlined. The tests verify the feasibility of the design and making corresponding improvements based on the test results plays an important role in this project. In this way, not only can problems be identified during the prototyping testing process, which greatly improves the quality of the final product, but also targeted modifications can be made without affecting the whole system (Guo, 2021).

In short, V-model provides instruction on how to design a system hierarchically and pays much attention on the tests. That is what this project requires and thus, V-model has been selected as the method of this project.

3.3 Method Application

The V-model method needs to be adjusted specifically to this project according to the former sub-projects results and the actual project situation.

Because this thesis project is not based on the blank background, instead, as mentioned earlier, there is requirement to combine both previous project products, so the “review phase” is indispensable. Between orientation phase and system design phase, and also between system design phase and sub-system design phase, it is time to review all existing files, test results and prototypes done by former students to find the correct track of combination. During these “review phase”, the main activities are to delve into those sub-projects and optimize the existing results, find out the useful parts which can be exploited into this thesis project.

During the integration and checking phases, it needs to consider the reasonable combination of two sub-projects products rather than focus on only one aspect. And for such kind of project – combination between software and hardware, there will be a long time needed (2 months or so) which is used to test all components and each subsystem and finally integrate them into one complete system.

In the V-model approach, feedback from experts and clients is also a significant factor that must be considered carefully throughout the entire V-model process. The recommendations will benefit the designer greatly in some respects, for example, they would contribute to figuring out the practical remedies for the project problems. Therefore, feedback needs to be taken into account in every phase.

3.4 Activities & deliverables during each phase

1) Orientation phase:

This phase contains detailed communication with the in-company mentor to understand the project requirements and expectations. In this phase, project overview and accessible information would be clear. Timetable (planning) of the whole project should generate in this phase to guide and monitor the process of project. Besides clarifying and making list of requirements, research proposal with system and the measuring system demo test plan are supposed to be finished.

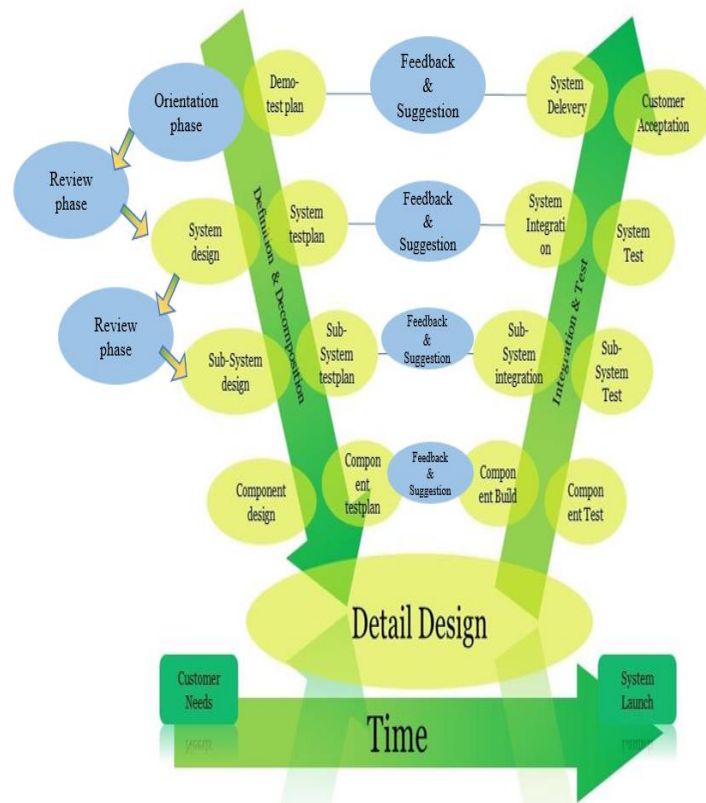


Figure 20 The applied V-model

Deliverables:

a. Research proposal; **b.** List of requirements; **c.** Project planning; Automatic switching electrode salt watcher system demo test plan

One sub-question shown below will be answered in this phase:

- What is the principle and operation progress of the existing measurement method using the traditional salt watcher device (Chauvin Arnoux C.A 6460)?

2) Review phase 1:

On account that this project has two previous sub-projects, review phase is required for reviewing all the results which had been done before. This includes the files, prototypes, circuit schematics, etc. Delve into two sub-projects and select the feasible part which can be used for this project, and also, research about the feasibility of recommendation provided by former researchers.

Deliverables:

- a.** Brief report about the analysis of previous project progress;
b. Embryo design ideas of the whole system

3) System design phase:

In this phase, the two systems designed in the previous projects will be reviewed and delved. Then focus on the transfer to building an open-source measuring system that can automatically measure all possible 4 (Wenner) electrode combinations. The design of the main system will be finished and the system description with flow chart, input & output diagram, system functions will be completed. In the end, the test plan of the entire open-source automatic switching measuring system will be written.

Deliverables:

- a.** System description; **b.** System function tree; **c.** System test plan

The former part of the question (for entire system) below will be answered in this phase:

- What are the description and functions of the entire system and sub-systems?

4) Review phase 2:

It is the second review phase, during which the focus is to review and refer to the sub-systems previously designed. Those existing sub-systems have referenced value and contribute to the sub-systems establishment in this project.

Deliverables:

- a.** Brief report about the analysis of previous sub-systems designed;
b. Embryo design ideas of the sub-systems

5) Subsystem design phase:

In this phase, the division of the system needs to be done according to the relevant requirements and start the design of the subsystems. Similar to that in the system design phase, the description and functions of the subsystems will be explained. Also, the test plan of each subsystem will also be finished.

Deliverables:

- a.** Sub-system description; **b.** Sub-system flow chart; **c.** Sub-system test plan

The latter part of the question (for sub-systems) below will be answered in this phase:

- What are the description and functions of the entire system and sub-systems?

So far, this sub-question has been solved totally.

6) Component design phase:

During this phase, each subsystem will be divided into components and the design of the component will be completed.

Deliverables:

a. Component list; **b.** The description and diagram of components; **c.** Component test plan

The sub-question below will be answered in this phase:

- What are the necessary components and their corresponding test plans of this open-source measuring system?

7) Component integration phase:

During this phase, components will be tested according to the test plan, generating the test results. After testing, analyze the result collected and make some adjustments for the tested components.

Deliverables:

a. Component test results; **b.** Checklist of the quality (if needed)

8) Subsystem integration phase:

The measuring device subsystem and automatically switching electrode subsystem will be integrated and tested according to their test plans during this phase. Then the test results will be analyzed and adjustment will be done if needed.

Deliverables:

a. Subsystem integration scheme; **b.** Subsystems test results

The sub-question below will be answered in this phase:

- What are the test results and actual function of each sub-system and do they accord with the expected design and results?

9) System integration phase:

In this phase, all subsystems will be integrated into the main measuring system. The main system will be tested according to the test plan and the test result will be analyzed.

Deliverables:

a. Main system test results; **b.** Actual functions (after testing) of main system

The sub-questions displayed below will be answered in this phase:

- What are the test results of the final integrated measuring system?
- What is the corresponding analysis of those final test results?

10) Acceptance phase:

It is the last phase during the whole project. During this phase, the final report will be finished and all the research questions will be given answers. The concept of the measuring system prototype will be demonstrated to the in-company mentor and the examiners. Finally, the portfolio, thesis report and project presentation will be written and made.

Deliverables:

a. Product portfolio; **b.** Final prototype of measuring system; **c.** Final report; **d.** Presentation

Chapter 4: Results

The outcomes of the projects will be mainly introduced in this chapter. The details of the system design including system overviews, input & output diagram and so on, will be demonstrated. Then the information of sub-systems and components will be introduced, which contains their respective design scheme, test plan and test results.

4.1 Requirements & Quality criteria

In this section, the requirements agreed by the client are collected and listed in Table 2 – Requirement list. Besides the necessary demands, there are some optional requirements, called wish, for the project and final system prototype. After the display of requirements, the quality criteria including 4 items of this project and their corresponding proof will be shown.

4.1.1 List of requirements

Table 2 Requirement list

Nr.	Requirement	Demand	Wish
1	Based on two sub-projects which were researched previously	✓	
2	Cost of the project is lower than 100€		✓
3	The system (hardware & software) is open source	✓	
4	The measured values (voltage, current) can be displayed on external connecting LCD or LED screen.		✓
5	The final soil resistance calculated can be displayed on external connecting LCD or LED screen.		✓
6	The soil resistance measuring sub-system connects with an electrode switching sub-system.	✓	
7	The 4-electrode set among 26 electrodes can be switched automatically in order and there are 23 possibilities in total	✓	
8	The entire measuring progress can finish within a few minutes.	✓	
9	The switching sequence of electrode set can be manually controlled		✓
10	The measuring system is easy to operate and the display interface is user-friendly		✓
11	The design is eco-friendly which would not generate harmless substances.		✓
12	Easy to install and integrate		✓

4.1.2 Quality criteria

Table 3 Quality criteria and corresponding proof

Detailed quality criteria	Proof
Price of each component + assembly labor cost (Totally less than 100 €).	Price list (in detail) including each component used in this project with their respective price and priced software (if needed).
Error:0-6% (Between the measured resistance value and the real resistance value).	Total measuring times is 23 in one measuring process and the difference between the resistance measured by this system and the results measured by professional instrument (C.A.6460) is less than 6%.
Total measurement time for 23 groups of electrodes is within few minutes.	The switch interval can be controlled by code. Since the measurement time for each group is so short that can be ignored and normally the switch interval is set at 2 seconds, which means the total measurement time for all groups is around $2 \times 23 = 46$ seconds.
The electrodes can switch automatically following control signals from the microcontroller.	Clear video of the switching function with at least one reliable witness or demonstrate the function live.

4.2 System design

In V-model, system design refers to the final deliverable design. The design is based on the requirements analysis and quality criteria. The system design mainly includes system input & output diagram and system description.

4.2.1 System overview

Shown in the diagram below is the input and output of the system. There are various factors of different types as the input and output, influencing the entire system. The input variables of automated salt watcher system include power supply, tested soil, etc. The output variables of automated salt watcher system include output current and voltage of the sensor, calculated resistance and so on.

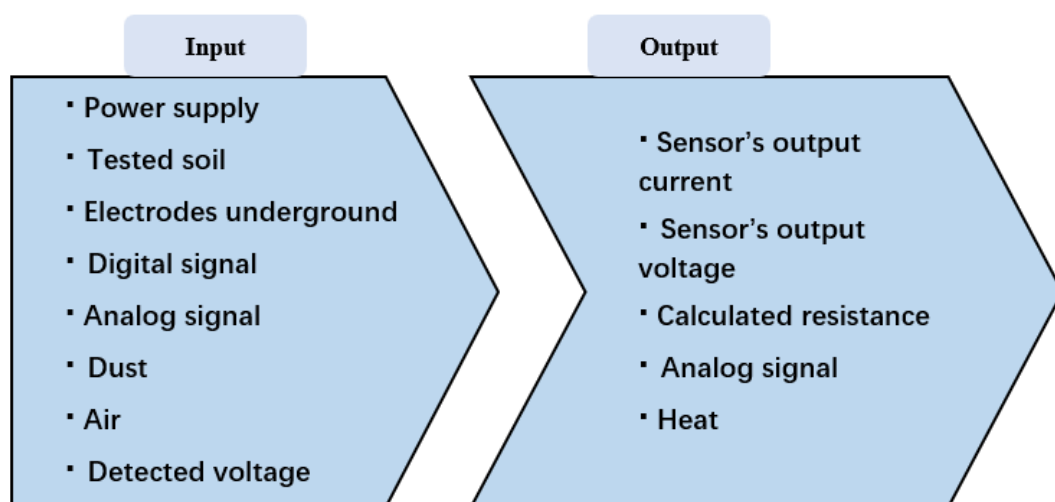


Figure 21 Input & Output diagram of system

According to the requirements of project, this automated salt watcher system boasts three main functions: soil resistance measuring, automatic electrode switch and measurement display.

The focus of system description is clarifying the external interactions with the system and as Figure 22 shown, the soil to be measured, environment, power source and user are four main external systems. In terms of the practicality of the project, inward and outward environmental factors have been taken into account. Z1, Z2 and Z3 represent the interactive influence between the automated salt watcher system and external soil to be measured.

Besides, U1 and U2 are the interaction between user and the entire system, while U1 means the user's control command and U2 means the system feedback to user. On the right, XD1 is the external power supply for the whole system.

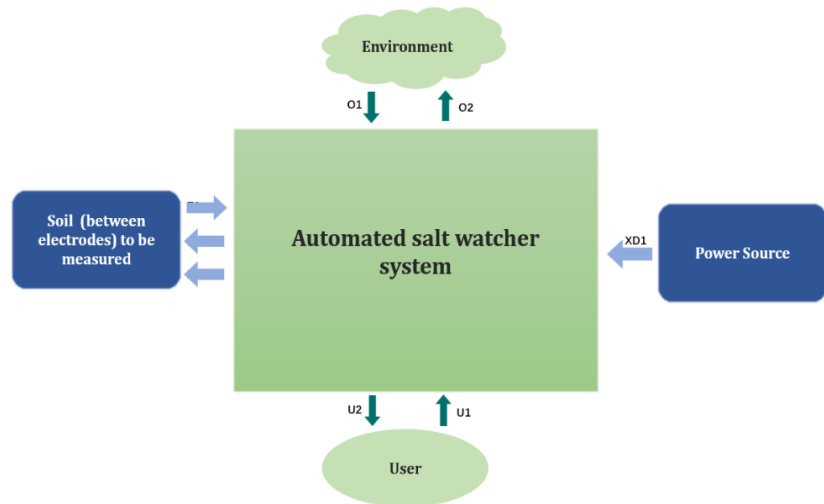


Figure 22 System overview

Table 4 Meaning of the unique ID & limitation of system

Unique ID			Long Name		
U			User interaction		
O			Collection of all environmental impact		
XD			Electrical DC signal		
XA			Electrical AC signal		
Z			Other		
Item	Representation	Symbol	Min	Max	Unit
O1	Inward environmental impact	\	\	\	\
O2	Outward environmental impact	\	\	\	\
XD1	Power for whole system	U	5	12	V
	Power for each component	U	0	600	mV
Z1	Soil to be measured (Resistance)	R	0	2000	Ω
Z2	Differential voltage	U	100	2500	mV
Z3	Frequency	f	\	800	Hz
U1	User control order	\	\	\	\
U2	Resistance value displayed in Arduino IDE Serial Monitor	R	0	2000	Ω

4.2.2 System test plan

Aimed at confirming the designed system fits the criteria and all functions execute successfully, system test is necessary to carry out. The system test plan guides the whole test process and ensures the test is within the proper experimental range.

For this project, in terms of the complexity of the final system prototype, it is necessary to firstly

build a system demo of which 3 optocouplers composed as the concept proof of the final system and implement the corresponding test of this demo. Secondly, the system consisting of all 23 optocouplers integrated into a PCB will be tested under ideal conditions, which means testing in the laboratory using ideal resistors. Finally, practical on-site test for the qualified system (PCB) prototype will be carried out, in order to check the system performance in actual measurement environment. Accordingly, the tests for the entire system are divided into 3 parts—system demo test, complete system prototype (PCB) test and field system prototype test.

a. The test plan of Automated Salt Watcher system demo can be found in Appendix XII——

[Automated Salt Watcher system \(demo\) test plan](#).

b. The test plan of Automated Salt Watcher system prototype (PCB) can be found in Appendix XII——

— [Automated Salt Watcher system in-lab test plan](#).

c. The test plan of Automated Salt Watcher system field test can be found in Appendix XII——

[Automated electrode-switch salt watcher system test plan \(at HZ SEA Lab\)](#).

4.3 Sub-system design

In this section, the overview and description of subsystems that consist of the entire measuring system will be demonstrated firstly. The holistic introduction is followed by the details of each subsystem design.

4.3.1 Sub-system division

The Figure 23 below visually displays the structure of the system and the interaction between the elements in system.

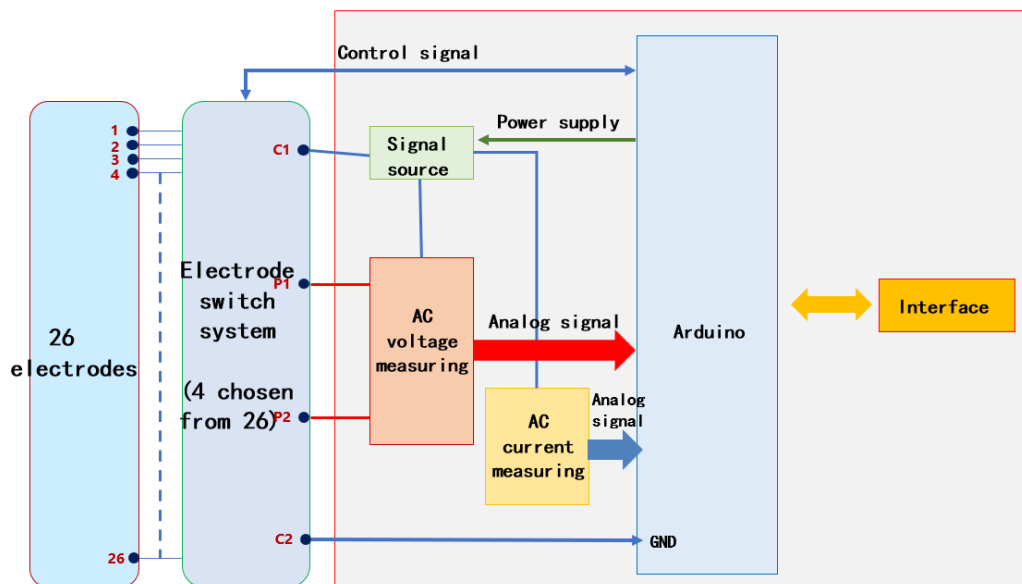


Figure 23 The basic structure diagram of system

As shown, firstly 4 electrodes are selected, named C1, P1, P2 and C2 respectively, by the switch system from the 26 electrodes. After that, the voltage drop between P1 and P2 as well as the current going through all electrodes will be measured, of which the analog signal will be transferred to Arduino to display for the user. Overall, this structure diagram instructs the system breaking down into sub-systems.

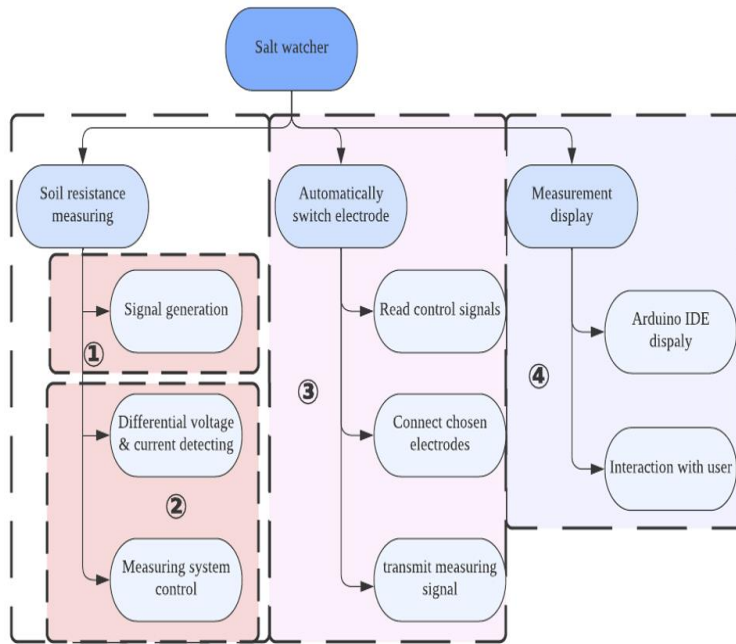


Figure 24 Function tree of automated salt watcher system

As shown in figure above, the automated salt watcher system has been divided into 4 modules: signal generation module, measuring module, switch module and display module. Since the measurement display function can be realized in Arduino IDE serial monitor, ultimately, the system composes of 3 sub-systems: signal generation sub-system, automatic electrode switch sub-system and voltage & current measuring sub-system. The right Figure 25 demonstrates the operation process of the system.

The function of each sub-system would be explained in this paragraph. For automatic electrode switch sub-system, it mainly consists of 3 aspects – reading control signals, connecting chosen electrodes (terminals) and transmitting measuring signals. This sub-system can realize the automatic switch among 26 electrodes in a specific order. For signal generation sub-system, it mainly uses Arduino Uno Board as power source to generate the AC square wave with the help of some voltage divider resistors. For the differential voltage & current detecting sub-system, the voltage and current sensors are the core components in this sub-system. The current and voltage changes through the resistor would be measured by this sub-system. For the display sub-system, several important parameters (such as voltage, current and resistance) obtained by the microcontroller would be shown to the user on the display screen.

4.3.2 Sub-system overview

The interaction and the interactive variables between each sub-system would be shown in the Figure 26 below. The XA1 means AC power from the signal generation sub-system to voltage & current detecting sub-system. The Z1 means the analog signal (Current going through and differential voltage) sends to the Differential voltage& Current Detecting sub-system. The Z2 means the digital signal (By way of analog-to-digital conversion) sends to the Control sub-system. For the XD1, XD2, XD3, they represent the DC power signal provided by the Control sub-system. The Z3 means the communication of digital signals between two subsystems. At last, the visual value of the resistance shown to the user is U1.

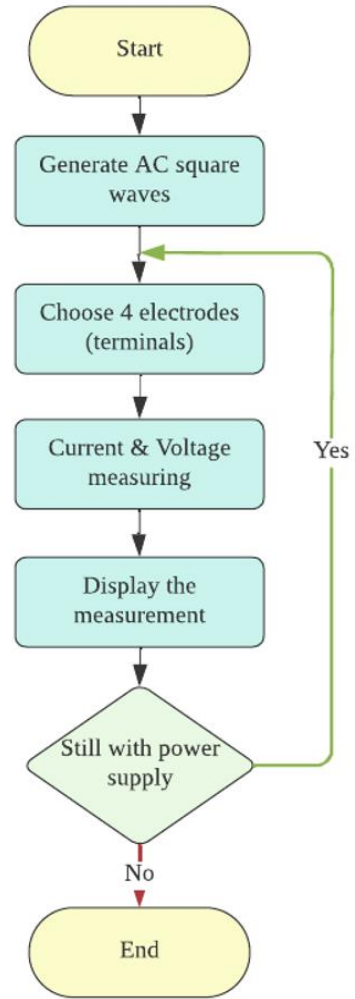


Figure 25 Subsystem flow chart

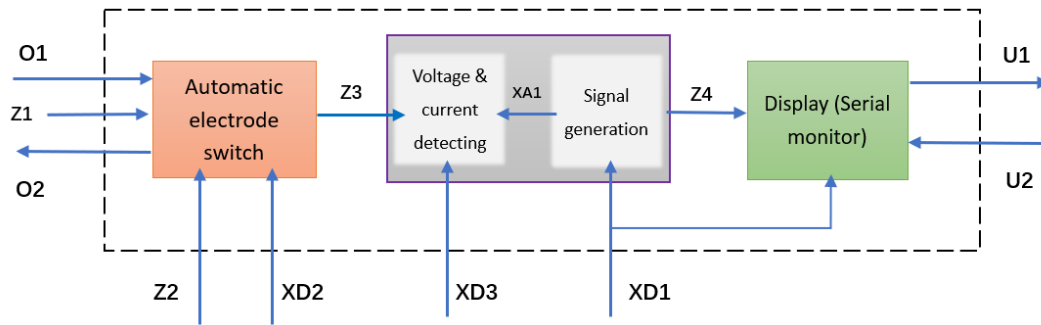


Figure 26 Sub-system overview—interaction and relation between sub-systems

Table 5 Limits of sub-systems

Item	Representation	Symbol	Min	Max	Unit
XA1	AC square wave signals to voltage & current measuring sub-system	U	100	2600	mV
	Frequency	f	100	3600	Hz
XD1	Power supply for signal generation sub-system and display sub-system				
	Supply voltage	U	3.3	5	V
XD2	Power supply for automatic electrode switch sub-system				
	Supply voltage	U	3.3	5	V
XD3	Power supply for automatic electrode switch sub-system				
	Supply voltage	U	3.3	5	V
O1	External environmental impact (contact resistor, soil conditions, etc.)				
O2	Impacts caused by system to environment				
Z1	Analog signal from electrode cable lines				
	Differential voltage	U	100	800	mV
	Induced current	I	0	100	mA
Z2	Digital signal for automatic electrode switch sub-system	Byte	\	\	\
Z3	Analog signal from electrodes chosen in automatic electrode switch sub-system to voltage & current measuring sub-system	Byte	\	\	\
Z4	Analog signal from voltage & current measuring sub-system to display	Byte	\		
U1	Displayed values in Arduino serial monitor	R	0	4700	Ω
U2	Command and operation from user	\	\	\	\

4.4 Sub-system I: Automatic electrode switch sub-system

The switch sub-system will be described with the assistance of sub-system overview diagram in this section. In addition, the test plan of switch sub-system will also be introduced briefly whilst more details of it are in the appendix.

4.4.1 Sub-system description

The most important function of this sub-system is to realize the automatic switch controlled by code in Arduino IDE within electrodes combinations. The user gives command by code to the sub-system

to determine the frequency of switch and how many groups of electrodes are chosen to measure. The 26 electrodes are connected with switch sub-system and the sub-system is responsible to select 4 electrodes at one time and connect them to the measuring circuit, detecting the current and voltage of electrodes. One piece of optocoupler TLP521-4 takes the responsibility for 4 electrodes, also regarded as one combination. As required from the client that there are 23 combinations

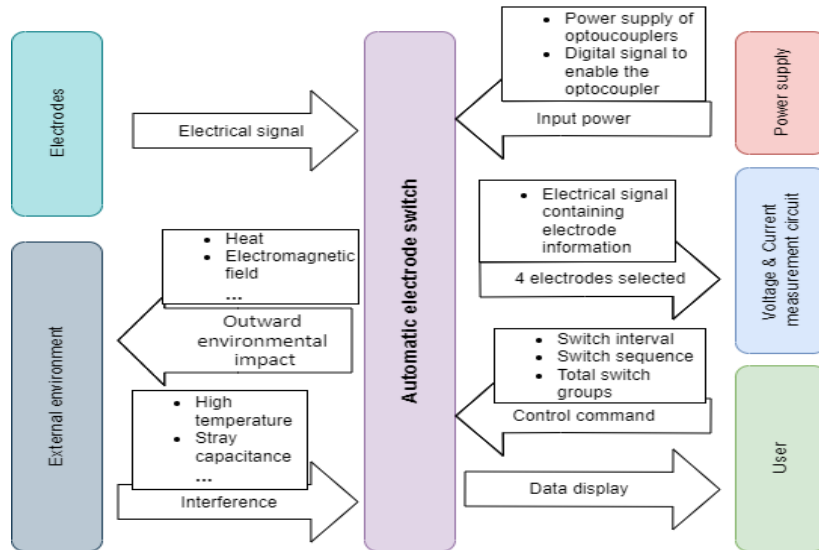


Figure 27 Automatic electrode switch sub-system

waiting to be measured among the 26 electrodes, so 23 optocouplers in total are needed.

As displayed in the left figure, there are 4 inputs as well as 3 outputs of automatic electrode switch sub-systems. This sub-system received electrical signals of all electrodes and selects 4 among those to transmit to the measurement circuit of the system. The switch command is determined by user, including the switch interval, switch sequence (among electrodes) and so on.

It is noticeable that this sub-system is supplied by two types of power: one is the DC 5V power source for optocouplers while the other one is the digital signal for enabling specific optocoupler. Finally, there are interactions between the automatic electrode switch sub-system and the external environment.

4.4.2 Sub-system test plan

This test plan is to illustrate how to test the automatic electrode-switch sub-system. The aim of this test is to verify whether the switch sub-system is able to stably switch within electrode sets. Because the goal of test is to prove the feasibility of concept design and system engineering approach V-model was applied in this project, the sub-system is inputted with ideal resistors instead of real electrodes. In this case, the input of the sub-system can be controlled flexibly and also, ideal testing conditions were created and the interference factors are excluded.

The test plan of automatic electrode-switch sub-system can be found in Appendix XII—[Automatic electrode-switch sub-system test plan](#).

4.5 Sub-system II: Voltage & current measuring sub-system

Voltage & current measuring sub-system is as important as the switch sub-system in this project. The measuring sub-system takes on the responsibility of measurement task in the circuit.

4.5.1 Sub-system description

The structure of voltage & current measuring sub-system is not complex and interaction of this sub-system and other elements is shown in Figure 28. The inputs of this sub-system are threefold: analog signals of electrodes chosen, AC square waves and DC power for ADS1115. The output of measuring sub-system is the measurement results to display for the user.

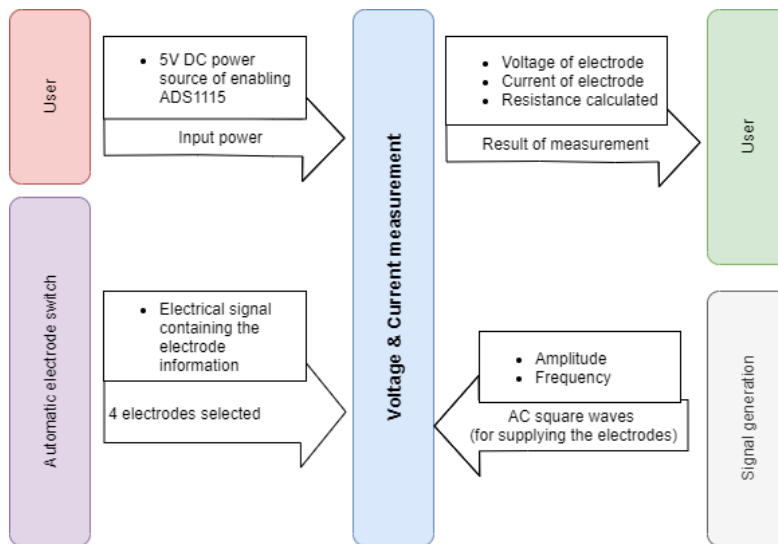


Figure 28 Voltage & current measuring sub-system description

To be more detailed, the electrical signal from those electrodes selected is from automatic electrode-switch sub-system and this signal contains the information of electrode to measure such as electric potential. As for the AC square waves rather than DC power, they are supply added to electrodes when measuring, aimed at eliminating the polarization effect occurring between the electrodes. The amplitude and frequency of AC square waves are changeable.

The result of measurement transmitted from voltage & current measuring sub-system to the user is composed of 3 parts. The voltage of electrode is measured by ADS1115 in differential mode: in differential mode of operation, the inputs act in pairs to measure the difference in voltage between the two inputs. The current detected is the current flows through the reference resistor but the value of it equals the current flows through the electrode because of the series connection. Finally, the corresponding resistance is calculated and displayed in Arduino IDE serial monitor to user.

4.5.2 Sub-system test plan

This test plan introduces the key points and process of the voltage & current measuring sub-system test. The aim of the test is to verify whether this sub-system has the function to stably detect the current flowing through the resistor to be measured and as well as the voltage across that under the AC square waves.

The test plan of Voltage & current measuring sub-system can be found in Appendix XII——[Voltage & current measuring sub-system test plan](#). The detailed test process and raw results are displayed in the Appendix XII Voltage & current measuring sub-system test result.

4.6 Sub-system III: Signal generation sub-system

The function of signal generation sub-system is to generate stable AC square waves. Using DC power supply for electrodes leads to polarization effect between electrodes, significantly influencing the accuracy of the test results. Thus, as required from the in-company mentor, an AC square wave generation circuit needs to be designed.

4.6.1 Sub-system description

Compared with automatic electrode switch sub-system, signal generation sub-system relates to the voltage & current measuring sub-system more. There is also power supply that is 5V DC from Arduino board for the signal generation sub-system. The whole operation in this sub-system can be regarded as a conversion of power supply, from 5V DC to AC square waves with various amplitude and frequency.

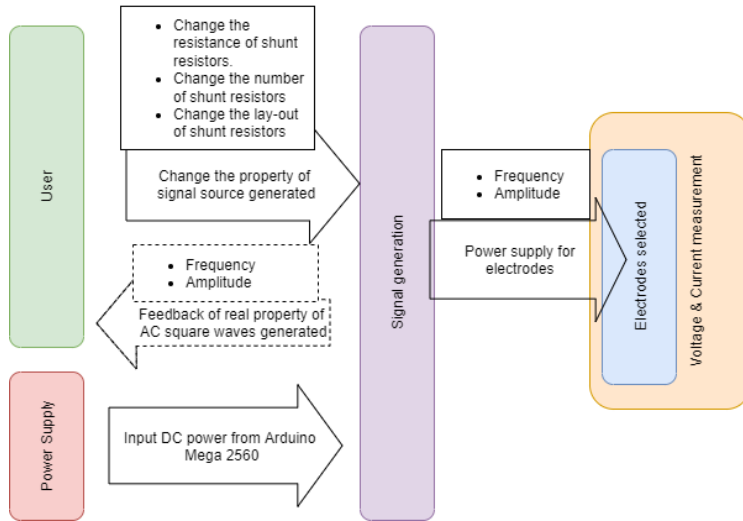


Figure 29 Signal generation sub-system description

4.6.2 Sub-system test plan

The aim of signal generation sub-system test is mainly to find out the properties of the equivalent AC square wave signal source generated by Arduino board with some voltage divider resistors. Also, test the stability and reliability of the AC square waves from the perspectives of frequency and amplitude. The AC signal generated in this sub-system will serve as the power source added to those electrodes when measuring.

The test plan of signal generation sub-system can be found in Appendix XII — [Signal generation sub-system test plan](#). The detailed test process and raw results are displayed in the Appendix XII Signal generation sub-system test result.

4.7 Component design & test

The component list including the details and descriptions of each component can be found in Appendix VII — [Component list](#). The schematics and properties of two core components, ADS1115 and TLP521-4 can be found in Appendix VIII — [Schematics and properties of core components](#).

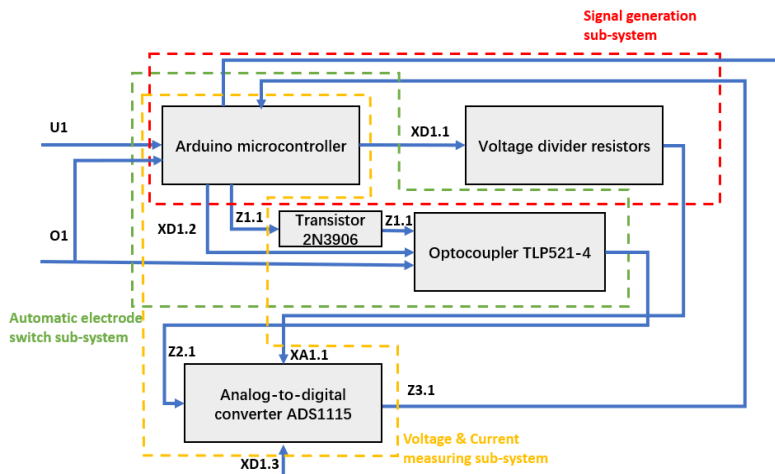


Figure 30 Data flow diagram of components in each subsystem

Before the component building and testing, the overview component design has been finished, as Figure 30 shows. There are 5 elements, Arduino board, voltage divider resistors, optocoupler TLP521-4, analog-to-digital converter ADS1115 and transistor 2N3906, in the diagram. the data flow relationships between components in every sub-system is clearly displayed in this diagram and this can be regarded as a summary of those

components described in the component design of every specific sub-system in the following sections.

The Table 6 below lists the limits of each component.

Table 6 Limits of components

Item	Representation	Symbol	Min	Max	Unit
XA1.1	AC square wave signals connected to analog-to-digital converter ADS1115	U	100	2600	mV
	Frequency	f	100	3600	Hz
XD1.1	Power supply from Arduino board to voltage divider resistors circuit to generate AC square waves	U	3.3	5.0	V
XD1.2	Power supply from Arduino board to each TLP521-4	U	3.3	5.0	V
XD1.3	Power supply from Arduino board to ADS1115	U	3.3	5.0	V
O1	External environmental impacts to Arduino board and optocoupler TLP521-4				
Z1.1	Digital control signal from Arduino microcontroller to optocoupler TLP521-4	Byte	\	\	\
Z2.1	Analog signal from optocoupler TLP521-4 to analog-to-digital converter ADS1115	Byte	\	\	\
Z3.1	Analog signal from analog-to-digital converter ADS1115 to the Arduino board	Byte	\	\	\
U1	Command and operation from user	\	\	\	\

4.7.1 Component design of switch sub-system

TLP521-4 optocoupler: The TLP521-4 can isolate switch circuit and measuring circuit, preventing the interplay between them. One optocoupler corresponds to one 4-electrode combination, so only one optocoupler is needed for each switch, the circuit is relatively simple. Because there are 23 possible combinations among electrodes in this project, 23 pieces of TLP521-4 are needed totally. The left side (LED side) of each TLP521-4 connects to the 5V DC power supply and digital output pin of Arduino microcontroller while the right side (phototransistor side) connects to 4 electrode and measuring component. These 23 optocouplers work one by one automatically controlled by code and so, 23 sets of 4-electrode combinations are selected and measured respectively.

2N3906 transistor: 2N3906 is a kind of small signal PNP transistor. In the switch sub-system, the function of this transistor is to make the optocoupler controlled by the high and low digital signal Z1.1 from the digital pin of Arduino board.

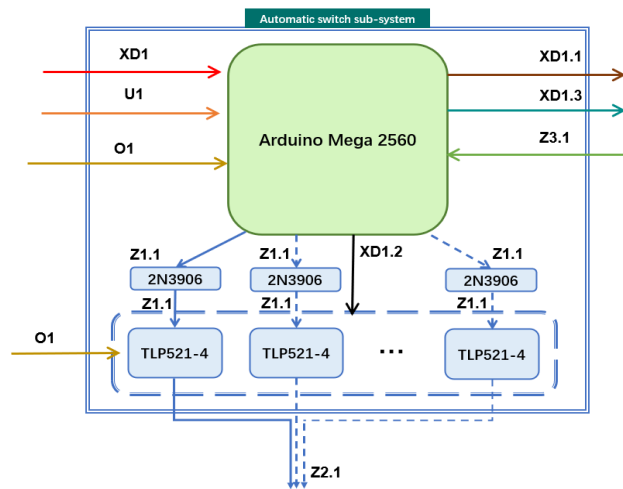


Figure 31 Component description of automatic electrode switch sub-system

As shown in Figure 31, automatic electrode switch subsystem is composed of Arduino Mega 2560 microcontroller and several TLP521-4 optocouplers. Environmental factors O1 influence Arduino Mega 2560 as well as TLP521-4. U1 is the user command to microcontroller. Arduino microcontroller is powered by external supply XD1 and serves as the power supply both for all TLP521-4 and the voltage divider resistors in signal generation sub-system. Z1.1 is the digital control signal from microcontroller to each TLP521-4 and Z2.1 is the analog signal from TLP521-4 to analog-to-digital converter ADS1115. For displaying the resistance measured, the Z3.1 is the analog signal containing the measurement information from ADS1115 to microcontroller.

4.7.2 Components of measuring sub-system

ADS1115 analog-to-digital converter: The ADS1115 is a kind of analog-to-digital electronics chip. The precision is 16-bit at 860 samples/second. This device can measure positive and negative voltages and it is noticeable that using differential measurement eliminates noise. In measuring sub-system, ADS1115 plays a role of voltage & current detector. In fact, ADS1115 detects two voltage values: one is the voltage drop of electrode while the other one is the voltage drop of a reference resistor of which the resistance is known. In terms of the resistance resistor and the electrodes to measure are in series, the current flowing through the resistance resistor equals to that of the electrodes. Therefore, it can be considered equivalently that ADS1115 detect both voltage and current of the electrode.

Figure 32 shows that voltage & current measuring sub-system consists of microcontroller Arduino Mega 2560 and detector ADS1115. Z2.1 is the analog signal containing electrode information from TLP521-4 of the switch sub-system. XD1.3 is the 5V DC power supply from microcontroller and XA1.1 is the AC square waves signal that is across the electrodes from signal generation sub-system. After measurement of ADS1115, the analog signal Z3.1 containing measurement results will be transmitted back to microcontroller to display.

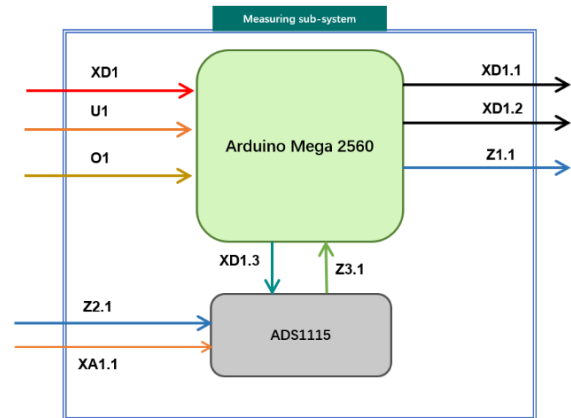


Figure 32 Component description of voltage & current measuring sub-system

4.7.3 Components of signal generation sub-system

Voltage divider resistors: Totally 3 or 4 resistors are used in signal generation circuit and these resistors are called voltage divider resistors. Since Arduino Mega 2560 board stably outputs around 5V on digital pins, it is feasible to configure the output voltage with the assistance of voltage divider resistors, generating AC square waves. The resistance of these resistors varies depending on the required amplitude of AC square wave (from 500mV to 2.5V).

XD1.1 is the power supply from Arduino microcontroller to voltage divider resistors to generate AC square wave signal XA1.1, which is the power used in voltage & current measuring sub-system.

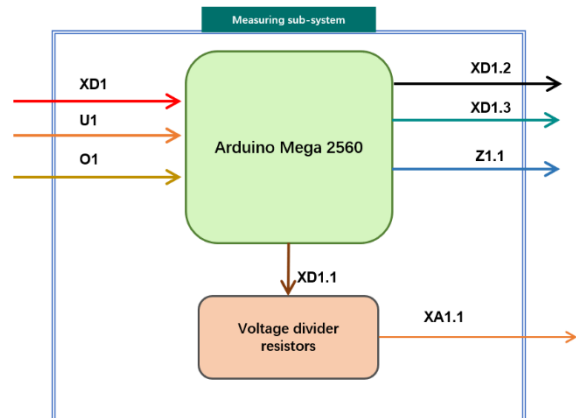


Figure 33 Component description of signal generation sub-system

4.7.4 Component test plan

The test plan of component ADS1115 can be found in Appendix XII——[ADS1115 test plan](#). This test is to confirm that whether ADS1115 could measure the voltage of the ideal resistor within the acceptable error range and transfer the data collected to Arduino microcontroller.

The test plan of component TLP521-4 can be found in Appendix XII——[TLP521-4 test plan](#). The aim of this test is to verify the isolation function and the switch function of the TLP521-4. The TLP521-4 will isolate the measuring circuit with AC square waves from other parts, so this test is the basis of further switch sub-system test and the final integrated system test.

4.7.5 Component test result

A. ADS1115 test result

In this test, 3 groups of resistors set-up are used to test the function of ADS1115. The configurations of resistance are 100-1000 Ω in series, 510-1000 Ω in series and 5100-2000-1000 Ω in series respectively. After comparing the voltage of the resistors measured by ADS1115 and the actual voltage measured by oscilloscope, the errors in each test group can be calculated and the calculation results have been drawn into bar chart displayed below. The detailed test process and raw results are presented in the Appendix VII ADS1115 test result.

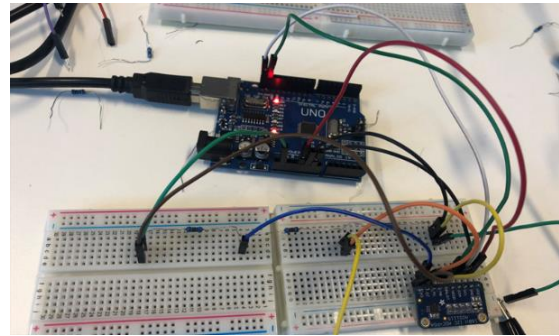


Figure 34 Test set-up of ADS1115

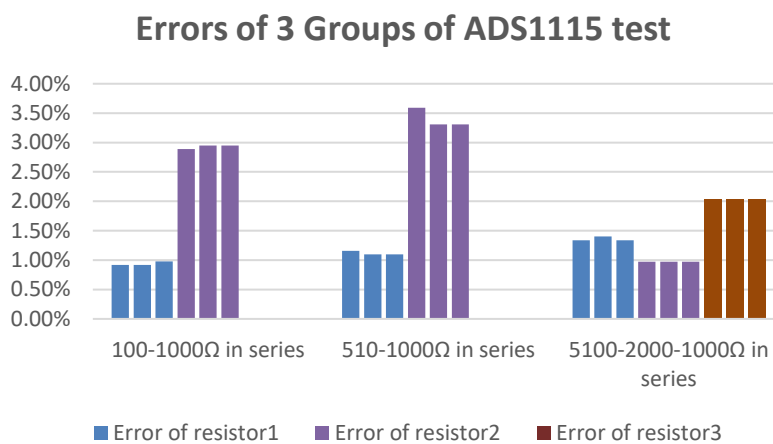


Figure 35 Bar chart analysis of ADS1115 test

It can be derived from the data in the tables above that if regarding oscilloscope as reference, all of the errors between values measured by ADS1115 and reference values are under 3.6%, which is within the required standard 6%.

B. TLP521-4 test result

After testing, it is proved that optical coupler TLP521-4 can work properly and for this project, this component can serve as timer switch by coding in Arduino IDE. The detailed test process and raw results are presented in the Appendix VII TLP521-4 test result.

As shown in the figure below, the multimeter was used to measure the potential from the lower end

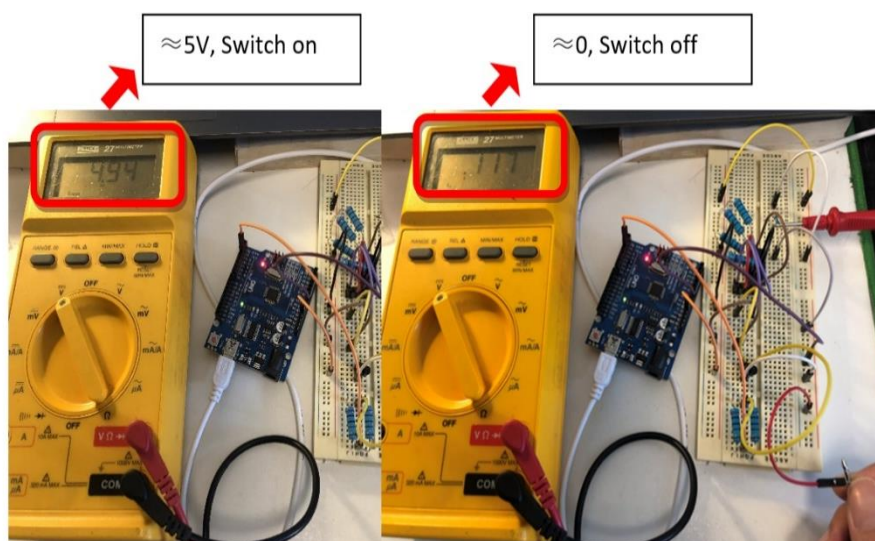


Figure 36 Test record of TLP521-4 test

of the resistor to the ground under the supply of 5V from Arduino board. When the potential is about 5V, it means the optocoupler TLP521-4 works at “ON” condition, the current going through the resistor and optocoupler to the ground. When the voltage drop is almost zero, it means TLP521-4 works at “OFF” condition.

4.8 Sub-system integration & test

Following the V-model, in this section, the integration scheme and process of each sub-system will be illustrated firstly.

Aimed at validating the feasibility of the sub-system integrated, sub-system tests had been carried out respectively and the relevant test results of each sub-system are displayed in the following sections.

4.8.1 Sub-system I: Signal generation sub-system integration & test

According to the previous research on the handheld measuring device C.A 6460, the signal power source for voltage & current measuring sub-system is required to be AC source to eliminate the negative effect of electrode polarization. There is one previous signal generation sub-system designed by one of the in-company colleagues, Mick van Eerd, as Figure 37 below shows.

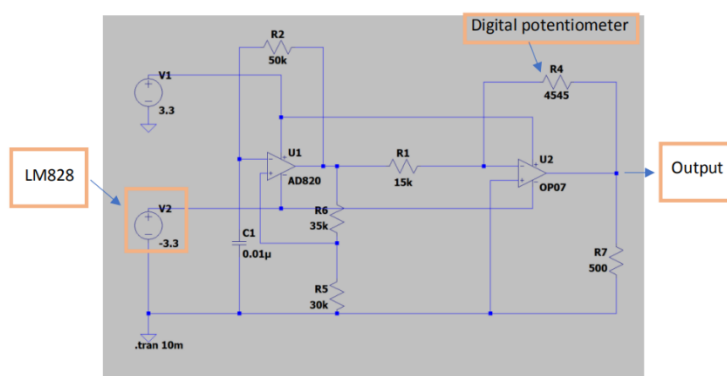


Figure 37 The soft simulation of signal generation circuit (Eerd, 2021)

Pinqi Guo researched and carried out related tests of this system. This circuit design needs to use several additional components such as operational amplifier AD820, OP07 and regulator LM828. What is more, the working state of the system is unstable (Guo, 2021). Therefore, there were still many adjustments and debugging work left to carry out of this circuit. Ultimately, Pinqi used a wave form generator to replace this signal generation circuit.

As recommended by Pinqi, at the beginning of this project, both signal generator SDG 1062X and signal generator module ICL8038 were tested as two options of signal generation sub-system. Their performances were excellent and the output AC square waves signals were stable as expected. However, they were external source and when the frequency was set at about 800Hz (design requirement), the ADS1115 which is the detecting device for voltage & current measurement could not work normally. The reason, after research, was that the sample rate of ADS1115 is too low and the frequency of 800Hz is too high. In other words, the AC square waves were too fast to detect for ADS1115.



Figure 38 Signal generator SDG 1062X

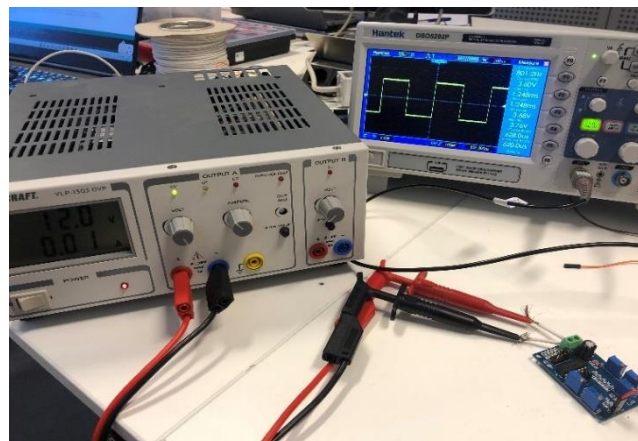


Figure 39 Test result of ICL8038

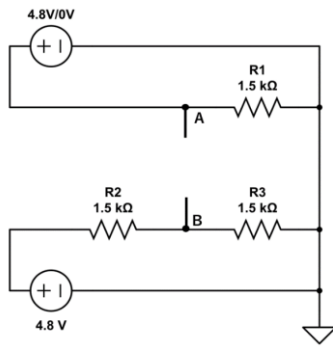


Figure 40 Signal generation circuit of 2.4V output

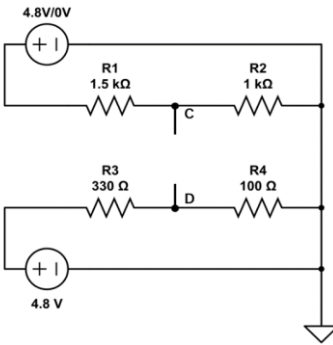


Figure 41 Signal generation circuit of 1.0V output

To solve this problem, after discussion with Haobo Guo, one of the in-company colleagues, a new portable signal generation sub-system that is based on Arduino board and several bleeder resistors was designed for this project. There were two configurations built of bleeder resistors of which the purpose is to generate two square wave signals with different voltage amplitudes.

Digital pins are most common and basic IO pins of Arduino and the output digital signal can be 0 and 1 which represent 0V low level and 3.3~5V high level respectively, depending on the type of Arduino board and the configuration of bleeder resistors. Output voltage of Arduino Mega 2560 is around 4.8V with 1kΩ resistor. Based on this, two circuits were configured using different bleeder resistors and the square wave signal with amplitude of about 2.4V is output between point A and point B whilst square wave signal with amplitude of about 1V is output between point C and point D. Besides, the frequency is adjustable by code in Arduino IDE.

Test result of signal generation sub-system

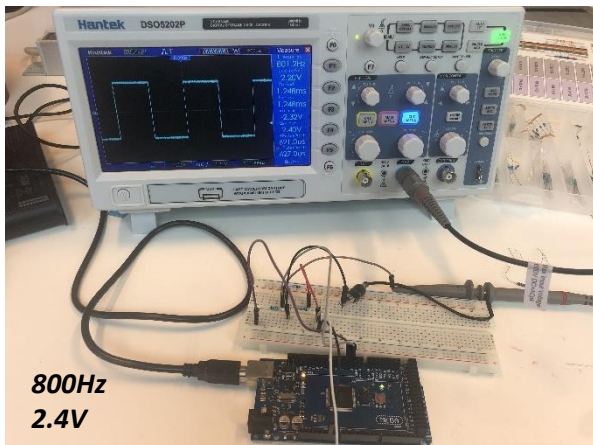


Figure 42 Test set-up and display of oscilloscope DSO5202P for 2.4V output

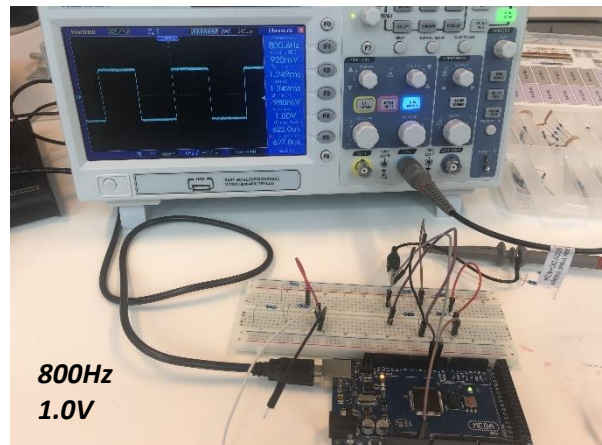


Figure 43 Test set-up and display of oscilloscope DSO5202P for 1.0V output

With the agreement from in-company mentor Mr. Goossen, an oscilloscope of which the type is DSO5202P was chosen to be the ideal reference device to read data of the signal generation sub-system. As Figure 42 and Figure 43 show, both these two kinds of AC square wave signals were outputted and detected by oscilloscope DSO5202P successfully. The raw test data and other bleeder resistor configuration are in [Appendix XII—test result of signal generation sub-system](#).

4.8.2 Sub-system II: Switch sub-system integration & test

The detailed discussion and determination process of the switching sequence between the electrodes are illustrated in [Appendix X](#).

Figure 44 below shows that for each TLP521-4, four resistors of 2kΩ, one resistor of 1kΩ, one resistor of 10kΩ and one transistor 2N3906 are used. After looking up the datasheet of TLP521-4, it was

known that the maximum forward voltage of LED in TLP521-4 is 1.15V. And the VDD is 5V as well as the minimum LED-side current that drives the optocoupler is 2mA, so the resistance of current-limiting resistor of each input terminal of TLP521-4 is: $R_L = \frac{V_{DD}-V_F}{I_F} = \frac{5.0V-1.15V}{2mA} = 1.9k\Omega$. In real sub-system integration, 2k Ω resistors were selected to use.

As for the selection of the pull-up resistor of transistor 2N3906, considering that the saturation

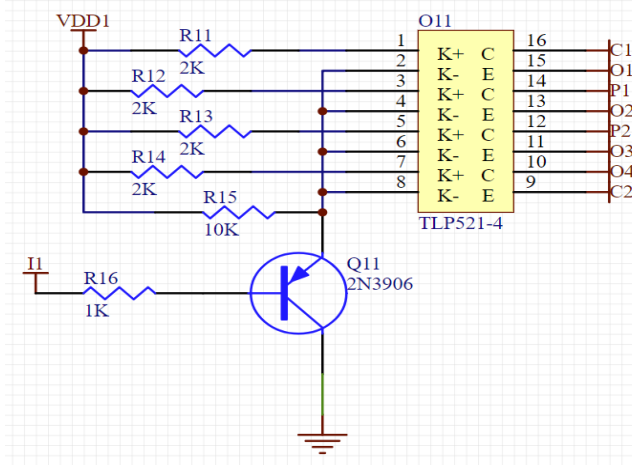


Figure 44 Core module of switch sub-system

voltage drop of transistor emitter-collector is 0.2V, the minimum resistance of pull-up resistor is: $R_{min} = \frac{V_{DD}-V_{EC}}{I_F} = \frac{5.0V-0.2V}{2mA} = 2.4k\Omega$. In real sub-system integration, 10k Ω pull-up resistor was determined to use because in this case, the emitter voltage of transistor can be increased to 10V in further research so as to increase the reliability and stability of the circuit.

The I1 terminal is connected to digital I/O terminal of Arduino. When the digital I/O terminal of Arduino is set at high level, the transistor is cut off and the potential of emitter terminal is high and at this moment,

optocoupler TLP521-4 does not work. When the digital I/O terminal of Arduino is set at low level, the transistor is at “on” working condition and the potential of emitter terminal becomes low, which leads TLP521-4 to work normally.

Theoretically, 23 optocouplers in total are needed for a complete switch sub-system to cover 23 possible combinations of electrodes. In terms of the complexity and non-operability of the set-up on breadboard, a switch sub-system containing only 3 optocouplers were integrated (as shown below), which can be regarded as the proof of the complete sub-system design. In final system integration stage, 23 optocouplers will be all integrated into one PCB for the final verification test.

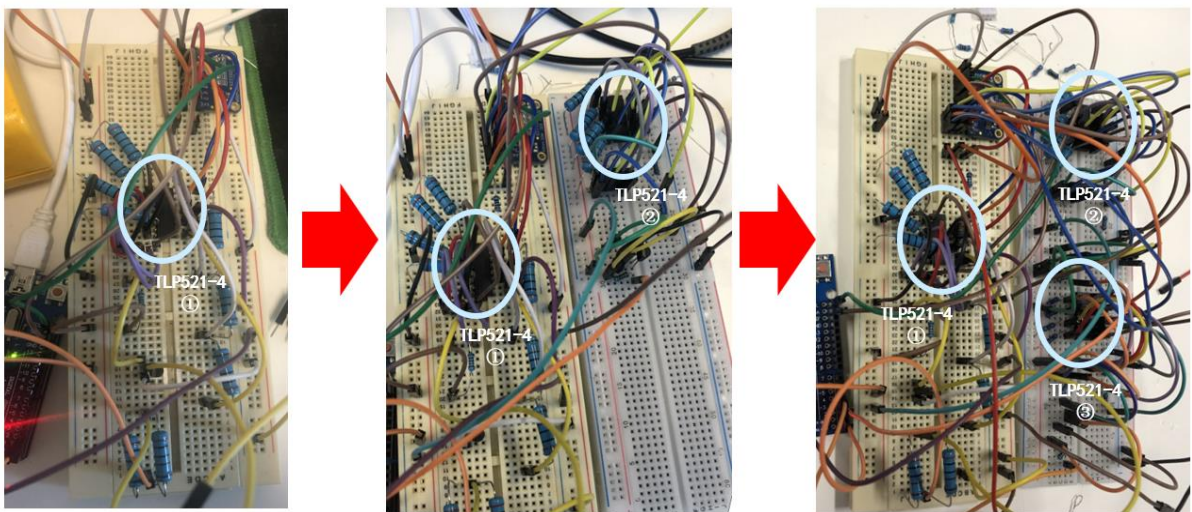


Figure 45 Integration process of switch sub-system on breadboard

Automatic electrode-switch sub-system test result

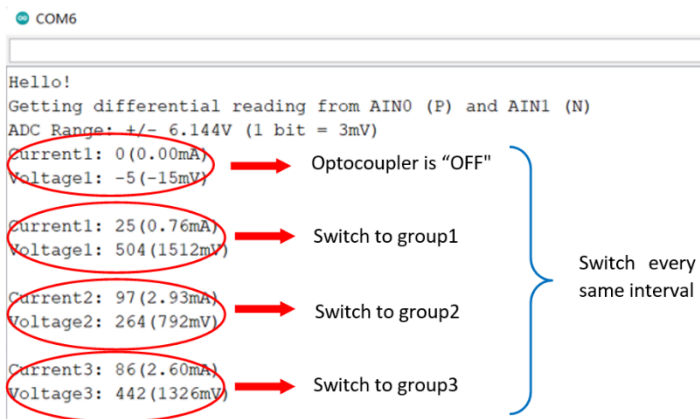


Figure 46 test results demonstration

As the left figure shows, 3 groups of resistors were used to test the switch function of this sub-system. In the first condition, the optocoupler keeps switched off, which means there is no current flowing through the circuit. Then optocoupler1 is controlled to switch on, so the current and voltage of the first group can be detected and displayed. After that the optocoupler switches off and optocoupler2 is controlled to switch on to measure and then turns to switch off. Finally, the optocoupler3

switches on to operate. The entire process keeps cycling until the power is cut off.

It can be concluded that the automatic switch sub-system can work normally as expected, switching automatically by code within the simulation resistor groups in spite of the fact that the accuracy of the values measured has not been proved yet.

4.8.3 Sub-system III: Measuring sub-system integration & test

The core component of voltage & current measuring sub-system is analog-to-digital converter ADS1115. As shown in the figure below, there are one 100Ω reference resistor and one resistor waiting for measurement in series connection. The reference resistor and the resistor to measure are both connected to ADS1115 respectively in a differential voltage detecting mode. Besides, an AC square wave source generated from signal generation circuit serves as the power supply of both the resistors. In this case, the differential voltage of the resistor to measure is detected by ADS1115 and with the current measured from the 100Ω resistor, the resistance of the simulation resistor can be calculated.

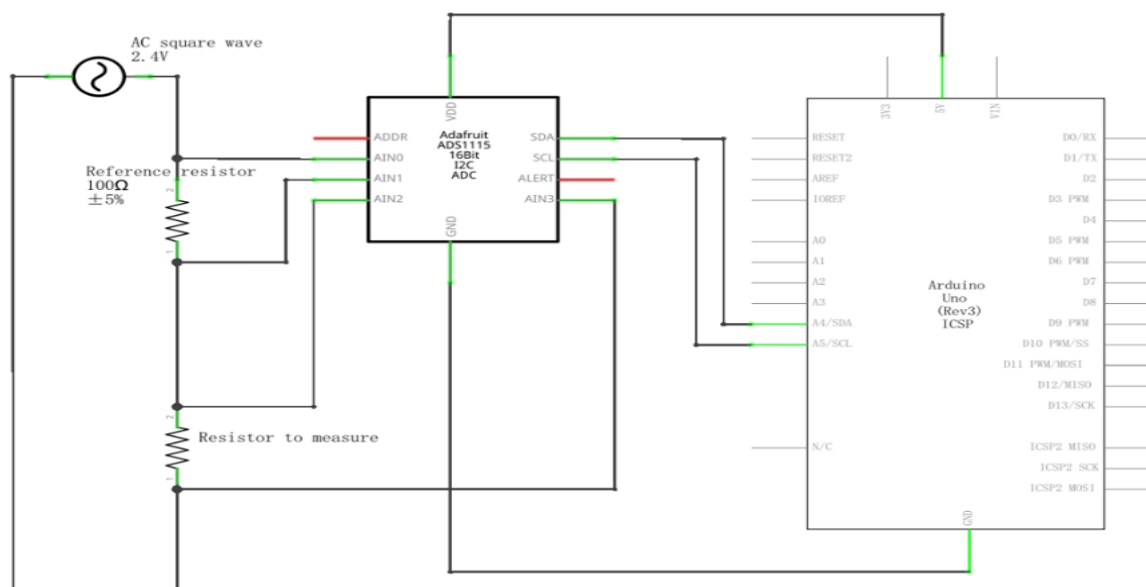


Figure 47 Measuring sub-system circuit schematic

Voltage & current measuring sub-system test result

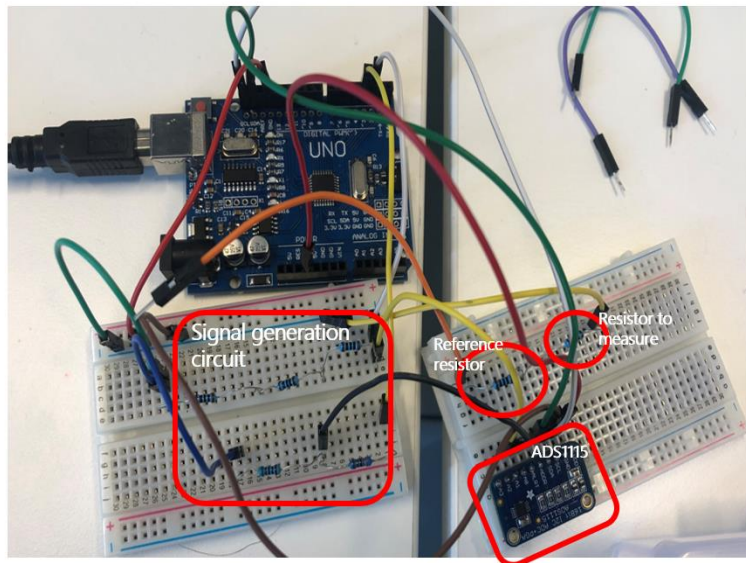


Figure 48 Set-up of measuring sub-system test

The on-site test set-up was displayed on the left (Figure 48). In this test, ADS1115 powered by Arduino board was separately tested 3 times to verify the accuracy of the measurement. 3 different resistors with the resistance of 2009.6 Ω , 511.2 Ω and 270.8 Ω respectively (measured by multimeter) were used. The results have been listed below and related errors are calculated. The raw test data are in [Appendix XII-- Voltage & current measuring sub-system test result](#).

Table 7 Test results and errors calculation of measuring sub-system

Nr.	Ref: 2009.6 (Ω)	Error 1	Ref: 511.2 (Ω)	Error 2	Ref: 270.8 (Ω)	Error 3
1	2010.15	0.03%	510	0.24%	269.62	0.44%
2	2009.17	0.02%	508.85	0.46%	268.26	0.95%
3	2009.66	0.00%	511.63	0.08%	273.36	0.94%
4	2010.15	0.03%	513.67	0.48%	269.86	0.35%
5	2009.66	0.00%	509.65	0.30%	271.48	0.25%
6	2009.91	0.02%	509.23	0.39%	269.62	0.44%
7	2009.87	0.01%	512.02	0.16%	271.03	0.08%
8	2009.39	0.01%	513.62	0.47%	271.63	0.31%
9	2009.91	0.02%	515.95	0.92%	272.22	0.52%
10	2009.59	0.00%	506.9	0.85%	269.86	0.35%

After the comparison of the values detected in the voltage & current measuring sub-system with the resistance measured by multimeter, conclusion can be obtained that all errors are lower than 1.00%, which means when measuring sub-system works separately, it has the capability to provide rather precise measured results.

4.9 System integration & test

The system integration is to combine signal generation subsystem, automatic electrode switch sub-system and voltage & current measuring sub-system into one complete system. After the integration, system was tested to validate whether the expected functions were realized ultimately.

4.9.1 Interaction between switch sub-system and measuring sub-system

The interactive part between switch sub-system and measuring sub-system is a critical part in system integration. These two sub-systems are the core of this project.

Figure 49 illustrates the interactive connection of one piece TLP521-4 and other components. For the ultimate test of the complete system, there will be 23 electrode combinations with 23 optocouplers. and each 3 resistors set used to would be parallelly connected to AIN1 and AIN2 sequentially. Every time when measuring, there is only one optocoupler switched on and one set (3 simulation resistors) connected to ADS1115 for measurement and the value calculated would be displayed in Arduino IDE serial monitor.

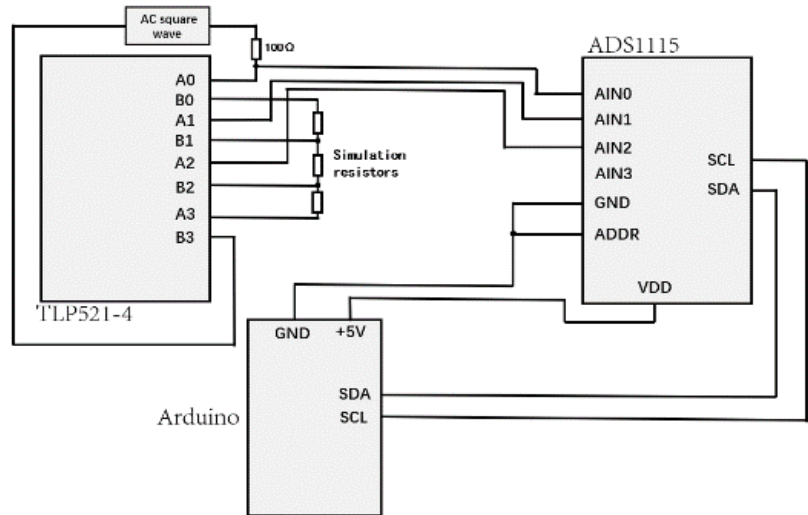


Figure 49 Schematic of interaction between switch sub-system and measuring sub-system

4.9.2 System demo (on breadboard) integration

Before the final integration in PCB, a system demo on breadboard was integrated. As mentioned in former chapter, this system demo only contains 3 optocouplers so there are 3 groups of data measured in one measurement. The feasibility of the system integration needs to be validated by this system demo and the system integrated into PCB cannot be manufactured unless the system demo passes the test.

System demo test result

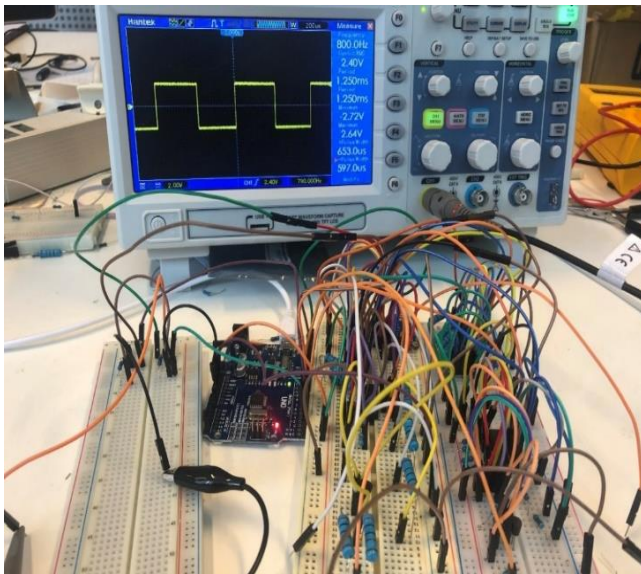


Figure 50 Set-up of Automated Salt Watcher System demo test

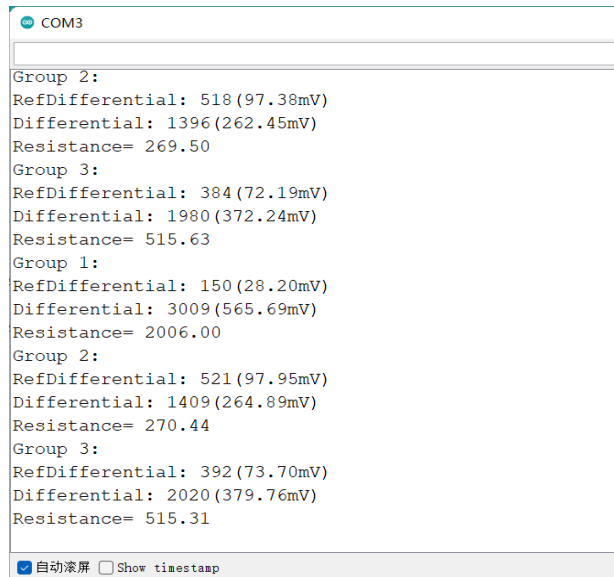


Figure 51 Screenshot of test results in Arduino IDE

Besides the AC test for system demo, DC test was also carried out and the test process and test results with detailed test results of AC test can be found in [Appendix XII-Automated electrode-switch salt watcher system \(demo\) test result](#). From Figure 51, two conclusions are obtained: the system demo can realize automatic switch function and keep cycling within 3 groups; the measuring part in the system demo works normally without interference from the switch function.

As for the error of test results, after comparison of the values measured by system and the actual

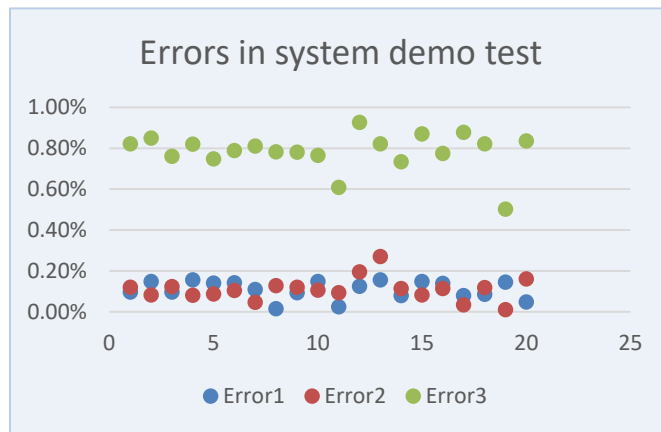


Figure 52 Scatter diagram of errors in in system demo test

values, it is gratifying that all errors of these group tests are lower than 1.0%, which proves that the combination between switch function with the usage of optocoupler and measuring function is successful. By analyzing this error line chart, it can be also derived that for resistors whose resistance is more than 500Ω , the interference is relatively small than those resistors that has lower resistance. In this test, the errors for two simulation resistors, 2000Ω and 510Ω , fluctuates at around 0.10% whilst the error for simulation resistor that is 270Ω fluctuates from 0.50% to 0.93%.

4.9.3 Printed circuit board (PCB) design of system prototype

The success of system demo test proved that both the system design and system integration scheme are feasible. So, the final production stage of PCB design and manufacture comes.

In PCB design, the connection between each optocoupler and 4-electrode is fixed. But the I1 terminal controlled by digital signal from Arduino is changeable, meaning that theoretically every order of switch can be realized by controlling the connection between the digital pins from Arduino board and I1 terminal of each optocoupler. Aimed at realizing 23 switches in one entire measurement activity, totally 23 optocouplers are used in switch sub-system, as shown below. The HD large images of PCB design document file and the circuit diagram are in [Appendix XI](#).

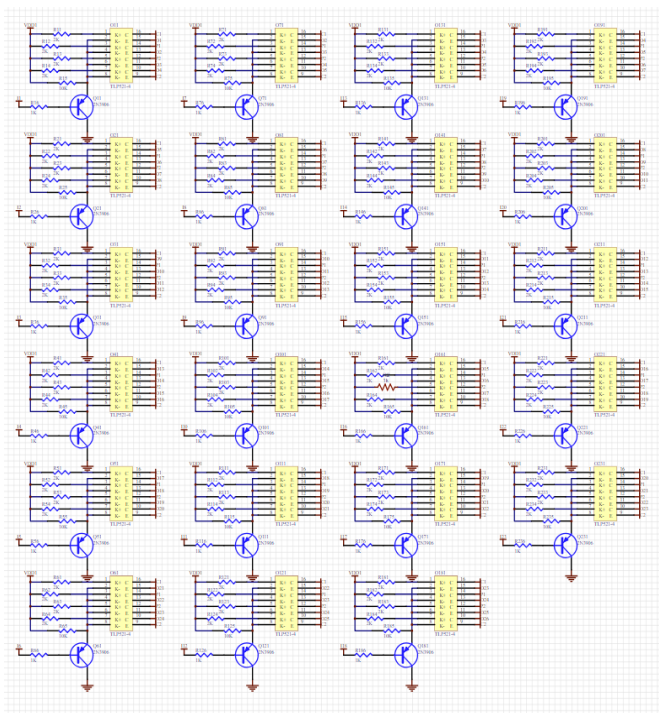


Figure 53 Partial of final prototype circuit schematic (23 optocouplers)

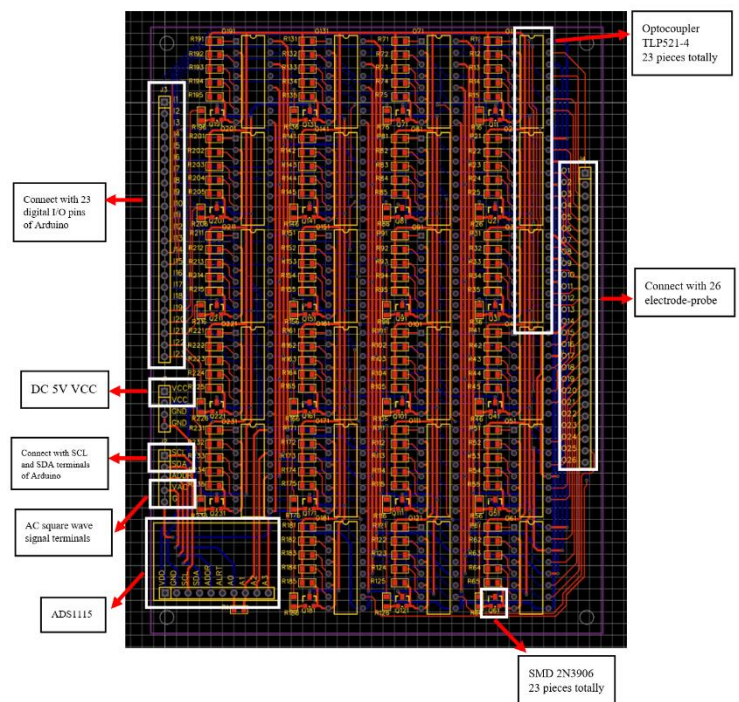
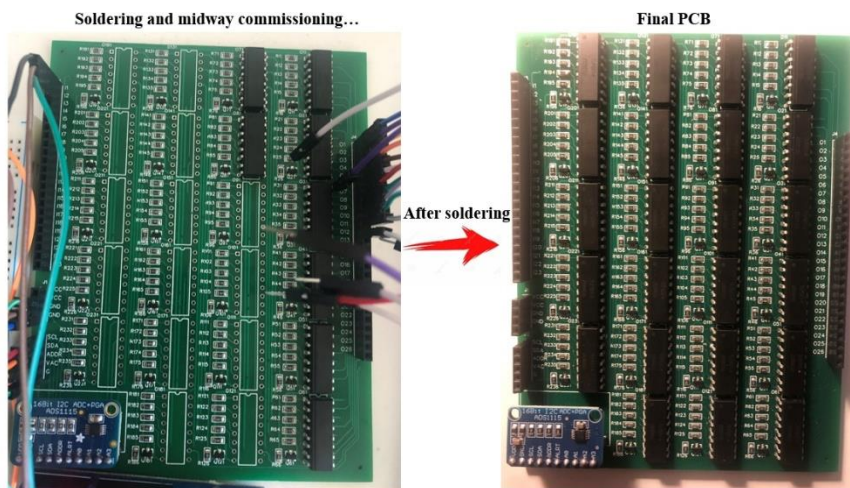


Figure 54 PCB design document file

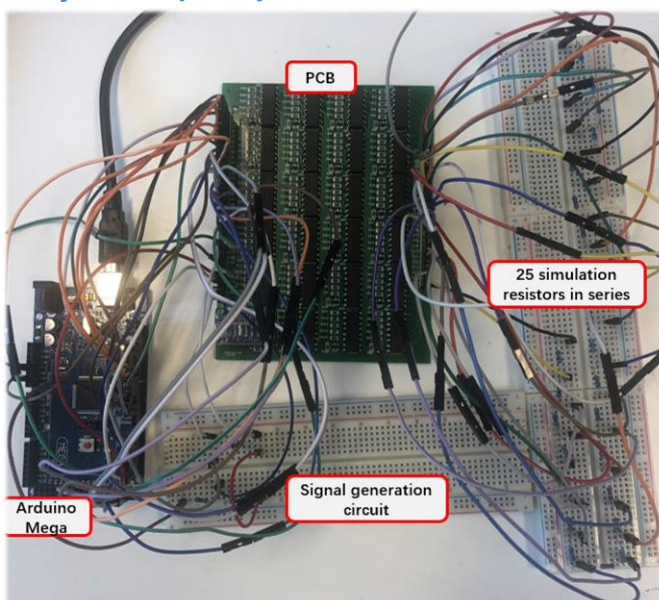
To save human labor, material resources and project cost, single surface mix assembly was applied



in this PCB design. As Figure 55 shows, in addition to ADS1115 and optocouplers, other small electronic components are all mounted directly onto the surface of PCB (SMT). The ADS1115 and 23 pieces of TLP521-4 are required to be soldered manually onto the PCB.

Figure 55 The soldering process of PCB

System (PCB) in-lab test result



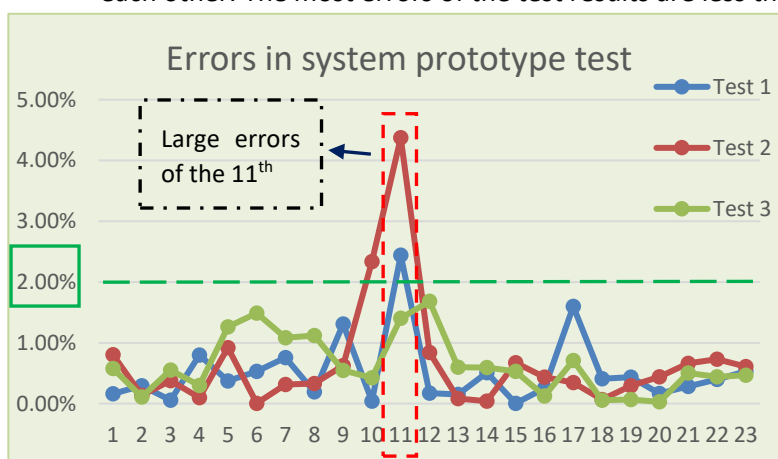
As shown in the figure 57 on the left, the final system prototype includes 4 parts – PCB, Arduino board, voltage divider resistors and simulation resistors. There are 25 resistors in total which are laid out in series generating 26 terminals. These 26 terminals are connected to the PCB simulating the connection between 26 electrodes and the PCB. 3 complete groups of test results of which there were 23 values respectively were recorded and analyzed. As comparison, the actual resistance of those 23 resistors were measured by multimeter and also listed in the excel table.

Figure 56 System prototype set-up overview

The raw test results are in [Appendix XII](#). After the test, it is visually to derive the conclusion from the line chart above that (Frequency: 800Hz and Amplitude: 700—2000mV) all sub-systems relating to the components successfully collaborated with each other. The most errors of the test results are less than 2.00% while they fluctuate during the

switch & measuring process. There are two relatively large errors seen from the figure and they are both the results of 11th simulation resistor. So, the reason of this peak might be the impacts of the environment, such as contact resistance, loose contact, stray capacitance, etc. In summary, despite the existence of few large errors, all errors are in the acceptable range of 6%, meeting the expected requirement.

Figure 57 Line chart of errors in system prototype (PCB) test



System prototype filed test result



Figure 59 Assembling when doing the field test

Figure 58 (left picture) Set-up of the on-site system test

On account of the difference of terminal type, there is not enough cables for connecting all terminals in the "white box" (in Figure 58) at the same time. So, with the permission of the in-company mentor, the on-site test is just to verify the accuracy of measurement. For the on-site prototype (green tank in the figure), there are 7 configurations of electrodes normally to test. Accordingly, the system on-site test also focused on the measurement of these 7 combinations.

Table 8 Test result analysis

Nr.	Wenner configuration	Measurement of system prototype (Ω)	Resistance measured by C.A 6460 (Ω)	Error	Pass the test?
1	50	19.63	18.48	6.22%	Yes
2	40	16.78	16.74	0.24%	Yes
3	30	79.55	21.6	268.29%	No
4	20	26.93	28	3.82%	Yes
5	10	44	49.4	10.93%	(almost) Yes
6	20B	65.68	15.26	330.41%	No
7	10B	17.85	17.09	4.45%	Yes

It can be concluded from the table that the measurement of 5 configurations had passed the test, even though one error slightly exceeded the expectation (within 10%). There were 2 incorrect measurements during the test. The reason why the errors were unstable and the cause of wrong measurements remain uncertain.

Here are some analysis and suppositions of that: **1.** Some environmental factors influence the operation of measurement. For example, the high temperature impacts the characteristics of Arduino microcontroller and some electronics components. **2.** The existing of stray capacitance affects the voltage measurement. **3.** The input voltage of the electrodes is too small (normally $\leq 100\text{mV}$), making detection difficult. **4.** Although the input power for electrodes is AC square waves, during each detection of the voltage the input power can be regarded as DC source at that moment, which may lead to slight polarization between electrodes.

Measurement of system prototype	Measurement of CA 6460
Group 1: RefDifferential: 740 (139.12mV) Differential: -145 (-27.26mV) Resistance= 19.63	
Group 1: RefDifferential: 651 (122.39mV) Differential: -109 (-20.49mV) Resistance= 16.78	
Group 1: RefDifferential: 621 (116.75mV) Differential: 493 (92.68mV) Resistance= 79.55	
Group 1: RefDifferential: 532 (100.02mV) Differential: 143 (26.88mV) Resistance= 26.93	
Group 1: RefDifferential: 501 (94.19mV) Differential: 220 (41.36mV) Resistance= 44.00	
Group 1: RefDifferential: 508 (95.50mV) Differential: 333 (62.60mV) Resistance= 65.68	
Group 1: RefDifferential: 668 (125.58mV) Differential: -119 (-22.37mV) Resistance= 17.85	

Figure 60 Screenshot of test result table

Chapter 5: Discussion

In this chapter, the test results will be discussed from two aspects. One aspect is evaluating the performance of the designed system in the tests. The other aspect is analyzing the reason why the system did not fully achieve the expectations in ultimate field test. In the last section of this chapter, there is an overall method judgement discussion.

5.1 Discussion for results

This system prototype has fairly achieved the expected goal when testing in the lab conditions using ideal resistors. However, in the process of testing and debugging in real conditions at HZ SEA Lab, some problems have been experienced and the system showed an unstable testing performance. Now discuss these test results from three perspectives: accuracy, reliability and validity.

5.1.1 Discussion about test results in lab conditions

In general, the in-lab tests, including system demo test and system PCB prototype test, both went smoothly and the results met the design requirements. In the system demo test, the measurements with error less than 1% can be obtained most of time. For system PCB test, 25 resistors were used to simulate the lay-out of 26 electrodes and in this test, the accuracy was slightly reduced, fluctuating from 0.2% to 2% mostly.

Accuracy analysis:

From the test results, it is manifest that whether of the system demo integrated onto breadboard or of the system integrated into a PCB, the measurement results are relatively accurate, meeting the design requirement that the error shall not exceed 6%. As for the slight accuracy difference of these two tests, it is probably caused by the hardware and wiring connection because the demo was integrated onto the breadboard whilst the entire system was integrated to the PCB.

Reliability analysis:

The reliabilities of system demo (on breadboard) and system prototype (on PCB) are different. Specifically, since many jumper cables and through-hole components were used for breadboarding the system demo, the reliability of this system is poor. It was difficult to troubleshoot due to human error and some bad connections problem. Sometimes the system demo could not work normally, leading to the switching function failure or wrong measurement. By contrast, the system integrated into the PCB was more reliable with good consistency and almost never went wrong after soldering.

Validity analysis:

Validity refers to whether a test measures what it aims to measure. The aims of these in-lab tests were both to measure the resistance of those ideal resistors laid out on the breadboard. In fact, the resistance was not directly measured by the system – there was an intermediate transformation process. Generally, resistance cannot be measured in an operating circuit. Therefore, taking voltage and current measurements and applying Ohm's Law is often used to determine resistance, which was the design ideas in this project. According to the test results, the validity had been established and checked respectively for these two tests.

5.1.2 Discussion about test results in real conditions

It is noticeable that in final on-site test, the system prototype performed differently from that in the laboratory. There were 7 configurations of electrodes tested and only 5 among them passed. The measurement data fluctuated violently, of which the errors were between 0% and 11%. Even two

errors reached 268% and 330%. This means the measurements of these two groups were incorrect totally. As for the professional resistance tester C.A 6460, it was capable to stably detect the resistance of soil between electrodes without interference from external factors.

Accuracy analysis:

The expected accuracy of system in lab testing conditions shall not be less than 94% while that of system in real testing conditions shall not be less than 90%. In other words, the error in field test is expected not to exceed 10%. From the test results displayed in Table 8, it is obvious there were several unqualified measurements. What is more, with the progress of the experiment and the increase of the ambient temperature, the experimental accuracy descended gradually.

After analysis, there are mainly 3 possible reasons causing such performance. Firstly, as Figure 61 shows, in order to have a stable voltage between P1 and P2, a constant current should be maintained in the measuring circuit. Since two photo-transistors A0-B0 and A3-B3 are connected in series in the circuit, and the typical saturation voltage drop of each photo-transistor is 0.2V and maximum is 0.4V, the voltage drop of the two transistors reaches almost 0.8V. In order to protect the electrode from damage, the amplitude of the square wave signal is required to be less than 2V, preferably less than 1V. In this case, so it is difficult to ensure the pathways of the circuit. Secondly, as mentioned before, on account of the sample rate limitation of the detector ADS1115, the AC square source needs to convert

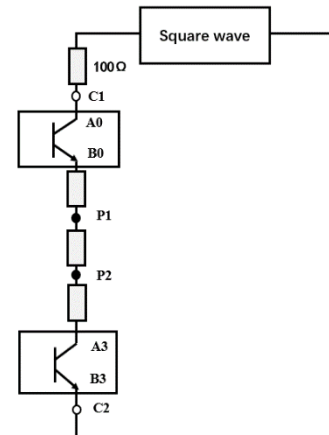


Figure 61 Equivalent circuit diagram

into DC signal source at each measuring moment of ADS1115. Otherwise ADS1115 cannot sample and detect normally. Thus, the short DC signals can still cause polarization of the electrodes, influencing the accuracy of the measurement. As the test time goes by, the polarization phenomenon becomes more and more serious, which also explains why the test results become more and more inaccurate. Thirdly, there are some realistic environmental factors affect the test results as well, especially the accuracy of the results. For example, stray capacitance and current in the electrode-probe damage the accuracy of the voltage detection of electrodes.

Reliability analysis:

The good reliability of system prototype with PCB had been proved during the in-lab tests. After several tests on site, the reason why the accuracy was getting lower and lower is not because of poor reliability, but because of technical and external factors.

Validity analysis:

The system accomplished the task of measuring resistance of the soil between electrodes in spite of some high errors. So the validity of the system prototype has been certified.

5.2 Discussion for V-model methodology

The V-model design method has successfully led this project over the past few months. The V-model guided reasonably all design phases including, system design, subsystem design, and component design in the first half of the project. Not only for the design, V-model also played a role in manage validation the system. From components to the entire Automated Salt Watcher system, every test was carried out based on the corresponding test plan and all test results were organized and analyzed. Overall, the whole project executed smoothly, and it can be concluded that V-model is a feasible technical guide for this project.

Chapter 6: Conclusion and Recommendation

In this last chapter, the conclusion of the final project outcomes will be clarified and related recommendations will be provided for further research.

6.1 Conclusion

As each sub-question has been solved, now it is time to answer the main question of this project: What is the design of an open-source measuring system that can measure the electrical resistance of underground soil using the principle of Wenner method, with several sets of automatically switching 4-electrode (less than 26 electrodes in total) combinations?

The final system designed uses Arduino microcontroller as central processing unit, external signal generation circuit as the AC power of measuring sub-system, ADS1115 as the circuit voltage and current detector and TLP521 as the electrode set switcher, with open-source code in Arduino IDE.

This design has relatively successfully completed the assignment task and basically achieved the expected goals. Compared with the previous ones, the automatic switching circuit and measuring circuit in this project have been innovated and improved. Of course, there were experiences of failure during the process of designing, testing and verification, but it has ultimately achieved excellent results through continuous innovation of ideas, adjustment of schemes and optimization of design.

The final system prototype completed the tests of using ideal resistors to simulate the electrodes and fulfill the requirement of accuracy, reliability and validity. However, the system prototype did not practically perform as expected when measuring the resistance of soil between the electrodes at HZ SEA Lab. The behind reasons were discussed in Chapter 5 but still uncertain. As for whether those supposes and assumptions are correct, further relevant research and demonstration are required.

6.2 Recommendation

- Add intermediate relay. As shown in the figure below, each optocoupler TLP521-4 connects with 4 intermediate relay output.

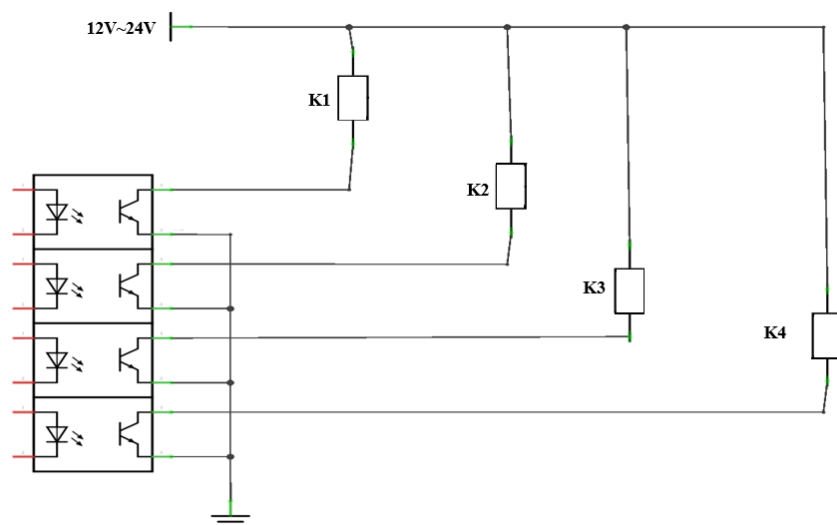


Figure 62 Relays layout of the switch sub-system side

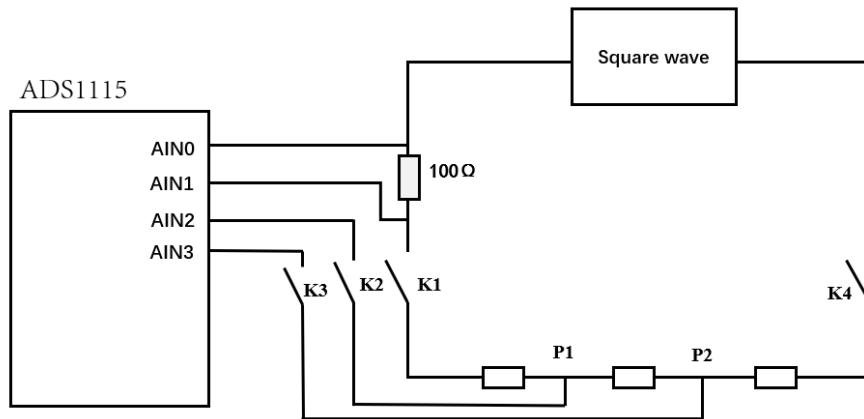


Figure 63 Relays layout of the measuring sub-system side

Functions of intermediate relays:

- (1) Anti-interference. In this way, the power supply voltage of the output intermediate relay can be increased to 12V or 24V to improve the anti-interference ability.
 - (2) Isolate automatic switch circuit and measuring circuit, eliminating the negative interaction between these two parts.
 - (3) Isolate on-site electrodes underground and the system circuit, reducing the negative interaction between them.
- The design of this project is to integrate measuring circuit and switch system into one PCB and use one external AC square signal source circuit. For further research, it could be a wise option to design two PCBs – One PCB contains the automatic switch circuit with output intermediate relays while another PCB, responsible for the measuring tasks, includes AC square wave generation circuit and current & voltage detecting circuit.
 - On account of that the sample rate of analog-to-digital ADS1115 is 8 ~860 samples per second (SPS), of which the default is 128SPS. It is too low to detect the AC signal whose frequency is high. Generally speaking, the sample rate must be at least twice the frequency of the sampled signal in order to output the sampling results stably. Therefore, it could be an option to research and apply another type ADS1015 with higher sample rate.
 - As mentioned before, the reference resistivity/resistance tester C.A 6460 measures resistance using (discrete) 10mA, 1mA or 0.1mA. Therefore, consider designing a stable constant current source as the power supply that has the capability to output those three types of current for the measuring sub-system. If it is too difficult to realize, it could also be feasible to find out solutions to applying one existing constant current power supply to the measuring circuit part.

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Appendix I : Search Plan of Theoretical Framework

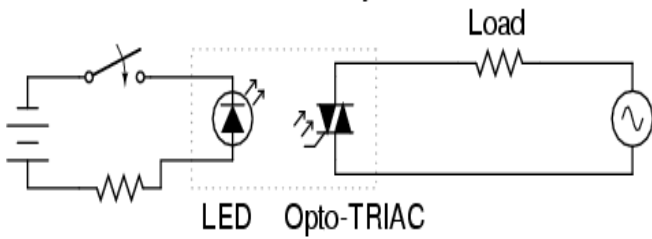
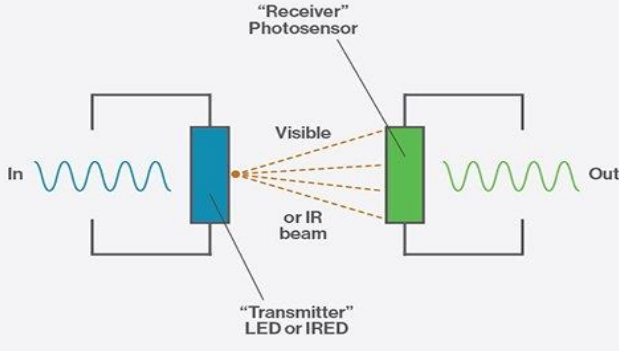
Table 9 Search plan

Nr.	Topic	Keywords:	Source:
1	Measuring system of previous project	AC square voltage, analog-to-digital converter, data display	Document; Image
2	Switch system of previous project	Switch, electrode, SPST, automatic, relay, analog	Document; Image
3	Switch selection	Contact switch, contactless switch, automatically, characteristics	Website; Scientific article; Forum; Image
4	Soil condition	Soil, salinization, conductivity, electrical resistance; the Netherlands	Document; Website; Scientific article; Expert
5	Measuring method and device	Wenner, electrode, electric, current, voltage, conductivity, handheld, device	Website; Document; Expert; Image
6	Practical testing/ experimental issues	Safety, operation, test, error, experimental site	Document; Website; Image
7	Arduino microcontroller	Single-Chip microcomputer, open-source, Arduino IDE, processing	Manual; Website; Literature; Forum
8	Price & Cost	Netherlands, market demand, manpower, human resource, electronics	Website; Literature; Image;

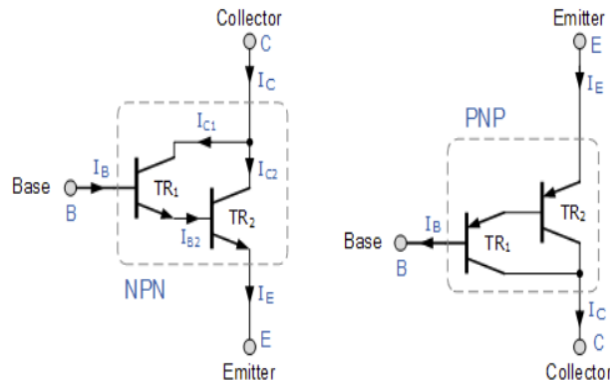
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Appendix II : Component selection -- Common contactless switch

Table 10 Common types of contactless switch

Type	Diagram	Characteristic	Application
Solid-state relay	<p><i>Solid-state relay</i></p> 	<p>A solid-state relay (SSR) is an electronic switching device that switches on or off when an external voltage (AC or DC) is applied across its control terminals. The function of the solid-state relay is isolating input and output and controlling high-power output current (Chen, 2008).</p>	<p>The most common application of solid-state relays is in the switching of an AC load, whether that is to control the AC power for ON/OFF switching, light dimming, motor speed control or other such applications where power control is needed, these AC loads can be easily controlled with a low current DC voltage using a solid state relay providing long life and high switching speeds (Electronics Tutorials, 2020).</p>
Optocoupler		<p>Optocoupler transmits electrical signals using light as a medium. It has the advantages of small size, long service life, no contact, strong anti-interference ability, insulation between output and input, unidirectional signal transmission, etc. It has a good isolation effect on input and output electrical signals.</p>	<p>Common applications for opto-couplers include microprocessor input/output switching, DC and AC power control, PC communications, signal isolation and power supply regulation which suffer from current ground loops, etc. The electrical signal being transmitted can be either analogue (linear) or digital (pulses) (Electronics Tutorials, 2020).</p>

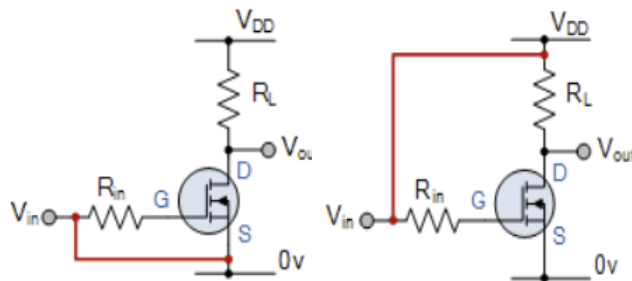
Darlington Transistor



The Darlington Transistor, which bears Sidney Darlington's name, is a unique configuration made up of two conventional NPN or PNP bipolar junction transistors (BJT) coupled in series. In order to create a more sensitive transistor with a significantly higher current gain that is beneficial in situations where current amplification or switching is required, the emitter of one transistor is linked to the base of the other (Electronics Tutorials, 2020).

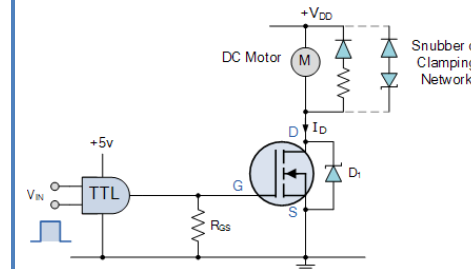
The base of the Darlington transistor is sufficiently sensitive to respond to any small input current from a switch or directly from a TTL or 5V CMOS logic gate. The maximum collector current $I_C(\max)$ for any Darlington pair is the same as that for the main switching transistor, TR_2 so can be used to operate relays, DC motors, solenoids and lamps, etc. One of the main disadvantages of a Darlington transistor pair is the minimum voltage drop between the base and emitter when fully saturated. Unlike a single transistor which has a saturated voltage drop of between 0.3V and 0.7V when fully-ON, a Darlington device has twice the base-emitter voltage drop (1.2 V instead of 0.6 V)

MOSFET

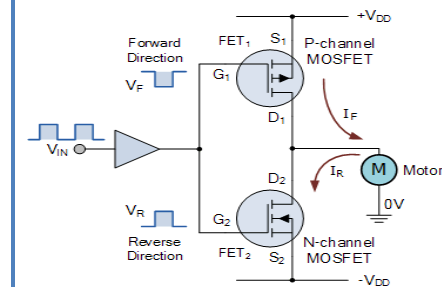


At present, MOSFET with various structures play an irreplaceable role in the field of high-power semiconductors. Besides, MOSFET's make very good electronic switches for controlling loads and in CMOS digital circuits as they operate between their cut-off and saturation regions (Electronics Tutorials, 2020).

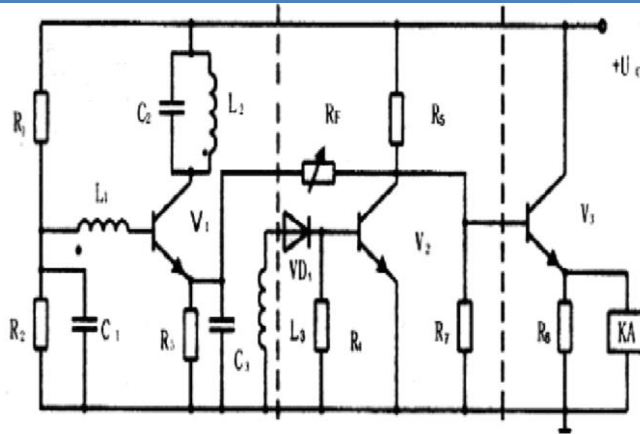
Simple Power MOSFET Motor Controller:



Complementary MOSFET Motor Controller:



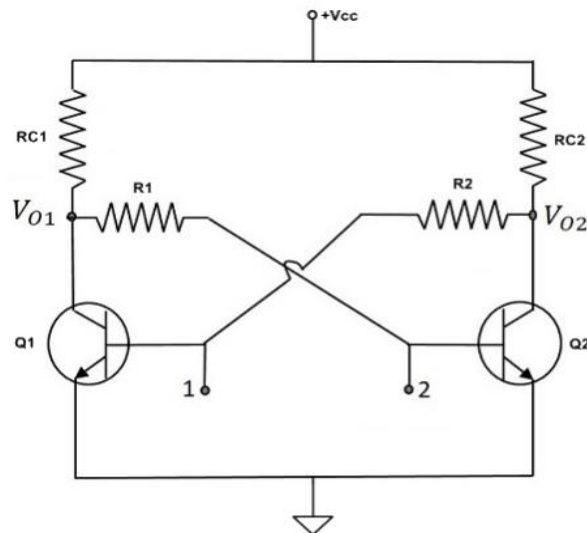
Proximity Switches



A proximity switch is used to determine how close an object is, or the proximity of an object. The proximity of an object is determined by using certain means such as magnetic, electric, or optical (Ashlin, 2020). So, these switches can be used to check the presence of an object. These switches are widely useful for many security processes. These switches can be used to check the motor rotation speed. Proximity switches can detect the approach of a metallic device part with the help of a magnetic or electromagnetic field.

- Level measurement and position detection
- Limit detection and thickness measurement
- Stack height measurement
- Conveyor systems and packing machines
- Mechanical engineering
- Paper, textile and plastic processing
- In printing machines
- Access control

Bistable Multivibrator



There are three types of multivibrator circuits: monostable, astable, and bistable. The bistable multivibrator operates like a pulse detector. When an electronic pulse is input to the circuit, the output will switch between two possible states (a high and low output voltage). This switching behavior does not trigger a free-running oscillation, in contrast to an astable multivibrator. There is some threshold for switching in a bistable multivibrator, which depends on the passives used in the regenerative feedback loop between the two transistors (Cadence | PCB DESIGN & ANALYSIS, 2022).

- These are some applications of the bistable multivibrator.
- It used in different storage devices and for counting of binary numbers.
- For frequency division in different circuits.
- It used for the production of different clock pulses.
- It used for different relay controller (Jones, 2020).
- It used in the different circuit as a toggle switch (Jones, 2020).

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Appendix III: Soil condition (Salinization & Conductivity)

III. I Soil Salinization

Salinization is the accumulation of soluble salts of sodium, magnesium, and calcium in soil to the extent that soil fertility is severely reduced. Soil salinization can negatively affect the growth of crops, and the direct impact is to reduce production. So far, there are mainly four reasons for soil salinization:

- First, the salt accumulated in the soil cannot be leached into the groundwater but accumulated on the surface of the soil.
- Second, the protected areas are often irrigated, the soil is wet for a long time, the crops grow vigorously, the evaporation of soil water and the transpiration of crops are very large, which promotes the accumulation of salt to the soil surface.
- Third, excessive fertilization increases the content of soil salt, especially the excess of acid radical ions of nitrogen fertilizer, acidifies the soil and activates some cations. These acid radical ions and activated cations gather on the soil surface with the movement of water.
- Fourth, the special environment formed by continuous cropping for many years limits the activities of beneficial microorganisms, while harmful bacteria become active, limiting the activities of beneficial microorganisms; harmful bacteria are active, which destroys the natural balance of soil microorganisms and inorganic nutrients and affects the decomposition of fertilizer.

Nowadays, soil salinization has become hard global issue that attracts the attention of many countries. Although the present situation is not very threatening, salinization might have a great impact on Dutch agriculture. Climate change and sea level rise will lead to the increase of seawater pressure and the decrease of fresh water supply in cultivated land (Starmans, 2018).

In the Netherlands, the current agricultural measures to adapt to these conditions focus on two main strategies: first, test the salt tolerance of existing crops and cultivated varieties to minimize damage; Second, look for new strong salt tolerant crops to make the best use of those abandoned salinized / salinized areas (Timmermans & Hospers-Brands, 2014). The development of saline alkali crops is a particular challenge for organic and sustainable agriculture, as saline alkali soils are usually located near (coastal) nature reserves sensitive to eutrophication (Timmermans & Hospers-Brands, 2014). Most of the salinized areas in the Netherlands are located near the coast, reclamation areas and permeable intertidal zones. Seawater (historically) exists in groundwater and is relatively close to the soil surface. Below - on the left is a map of the world's soil salinization; On the right is the average chloride concentration of surface water in July of the dry year (2011) in the Netherlands.

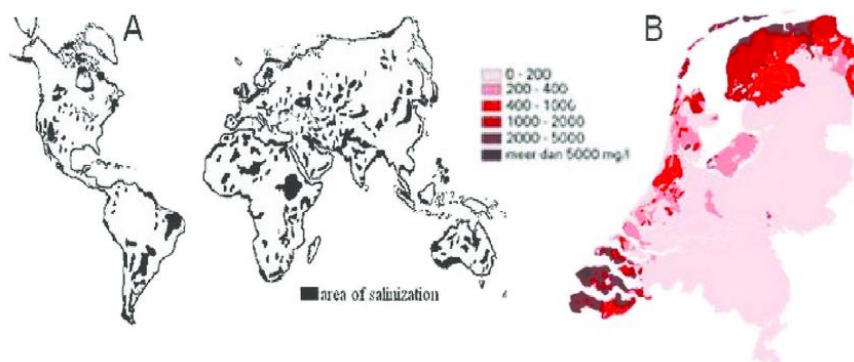


Figure 64 World map of soil salinization; B: Average chloride concentration (mg/L) of surface water in July during a dry year in the Netherlands (Timmermans & Hospers-Brands, 2014)

III. II Soil Conductivity

Soil electrical conductivity is an indirect measurement that is linked to a number of physical and chemical properties of the soil. Electrical conductivity is the ability of a material to conduct (transmit) current, which is generally measured in milli Siemens per meter (mS/m) units (Barbosa & Overstreet, 2015).

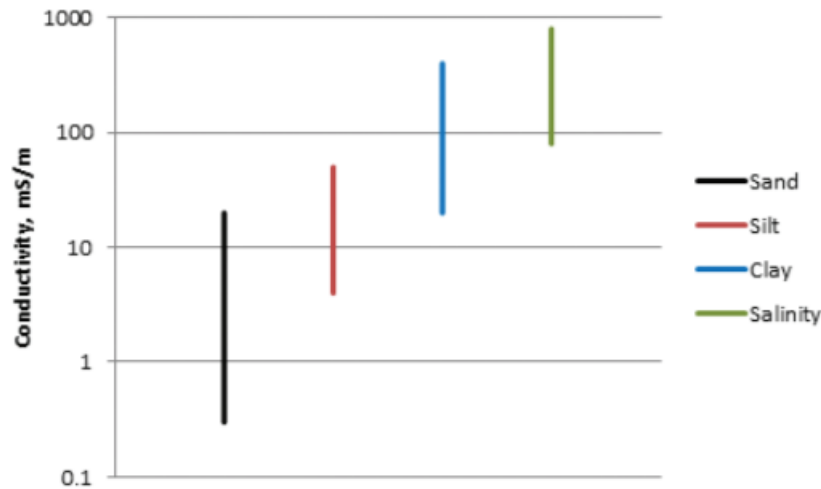


Figure 65 Conductivity values of different soil materials (Barbosa & Overstreet, 2015)

Soil conductivity is an important metric for assessing soil health. It has a clear impact on a variety of factors, including agricultural yields, crop appropriateness, plant nutrient availability, and so on. It also has to do with the activity of soil microorganisms, which has an impact on essential soil processes like the release of greenhouse gases like nitrogen oxides, methane, and carbon dioxide.

How can you determine conductivity of soil? In the case of experimental testing, the salinity of the soil sample is usually checked first, and then the standard conductivity at 25°C is measured. After that, using the mathematical statistics method, the regression analysis of soil salinity and standard conductivity is performed, and the regression equation is constructed. The return equation and standard conductivity show that.

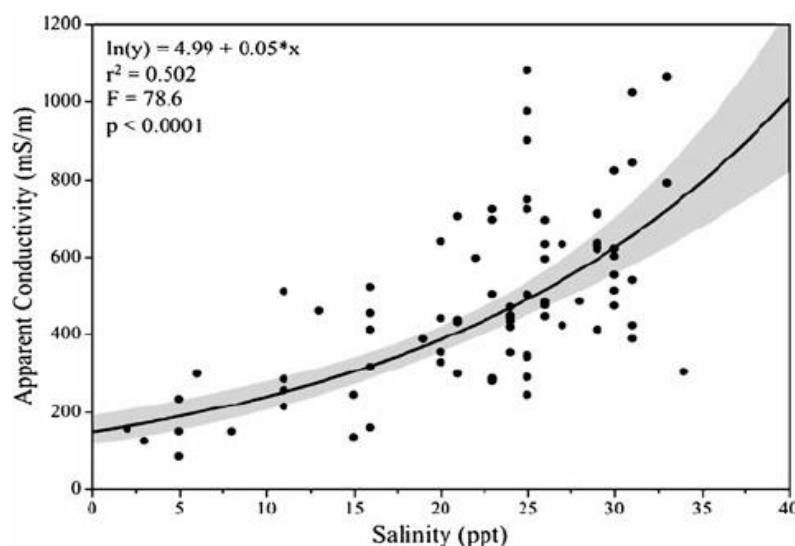


Figure 66 Relationship between Salinity and Apparent Conductivity (Moore, Burdick, Peter, & Keirstead, 2011)

The most common “measures” of salt concentration are really estimates based on soil and water

solution electrical conductivity. In addition, measuring electrical conductivity is likely to be used to determine soil salinity (as shown in Figure 66 above).

Table 11 Classification of soil salinity based on Electrical Conductivity (Moore, Burdick, Peter, & Keirstead, 2011)

Salt free	$EC_e < 4$	No visible salt on the soil surface. Crop growth remains uniform.
Slightly saline	$4 < EC_e < 8$	Visible salt on the soil surface. Crop growth is uneven and patchy.
Moderately saline	$8 < EC_e < 15$	Salt is fairly visible on the soil surface. Plant growth is very patchy and restricted.
Strongly saline	$EC_e > 15$	Soil surface is fluffy Salt is fairly visible Soil supports indigenous vegetation Salt tolerant crops are possible to grow

Soil electrical conductivity (EC) has been used as an indirect predictor of the quantity of nutrients absorbed by plants and salt levels, although it has no direct effect on plant growth. Salt content, organic matter, cation exchange capacity, soil texture, soil thickness, nutrients (e.g., nitrate), water retention capacity, and drainage conditions have all been measured using EC. EC is used to demarcate management units, classify soil types, and estimate soil fertility and crop yields in site-specific management and high-intensity soil surveys. Farmers can utilize EC maps to apply various management strategies (such as nitrogen fertilizer) to plots with various soil types, for example. High EC is linked to high levels of nitrate and other chosen soil nutrients (P, K, Ca, Mg, Mn, Zn, Cu) in some management units. High salt sensitivity (high EC) affects the majority of bacteria. With the exception of saline plant (salt-tolerant) bacteria, actinomycetes and fungus are less sensitive than bacteria. With increased EC, microbial activities like as respiration and nitrification reduced.

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Appendix IV: Introduction of Chauvin-Arnoux-C. A-6460

This instrument is made up of various parts that make it easy to use:



- A single pushbutton (for activation of measurement)
- An automatic switching system
- A large-size backlit liquid crystal display
- Three LEDs (to indicate the existence of defects that might invalidate the measurement result)
- Four colored screw terminals to simplify connection of the leads
- A captive connection strap

The left picture (Figure 67) is the top view of the interface of this instrument, and it is manifest that there are quite few buttons on it and the display area is also quite simple.

Figure 67 Overview of the C.A 6460 device (C.A 6460 & C.A 6462 User's manual, 2018)

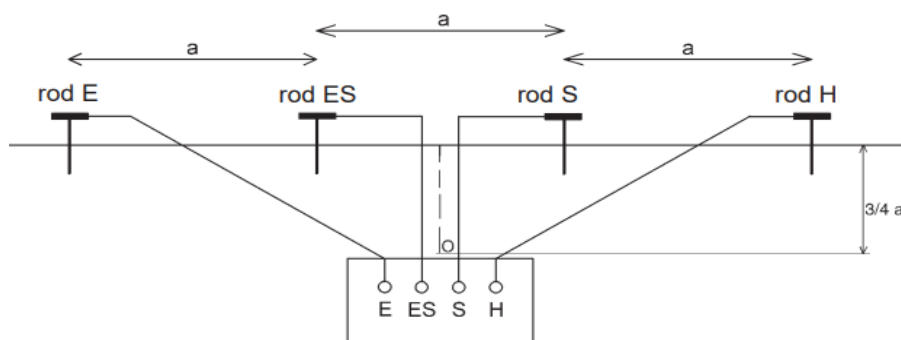


Figure 68 Wenner method used in C.A-6460 device (C.A 6460 & C.A 6462 User's manual, 2018)

The measuring method of this device is also the Wenner method, which is already mentioned and demonstrated earlier in this chapter. According to the actual situation, the best location and the shape of the earth point is known. The figure below is the sketch of the Wenner method principle using for Chauvin-Arnoux-C. A-6460 (C.A 6460 & C.A 6462 User's manual, 2018).

The position of the four measurement terminals is shown in the figure. The distance between each rod is equal to a (Meter). The ground resistivity of the point O could be calculated by the following formula (C.A 6460 & C.A 6462 User's manual, 2018):

$$\rho = 2\pi R a$$

ρ : Ground resistivity ($\Omega \cdot m$);

R : Resistance (Ω);

a : The distance between each rod (m)

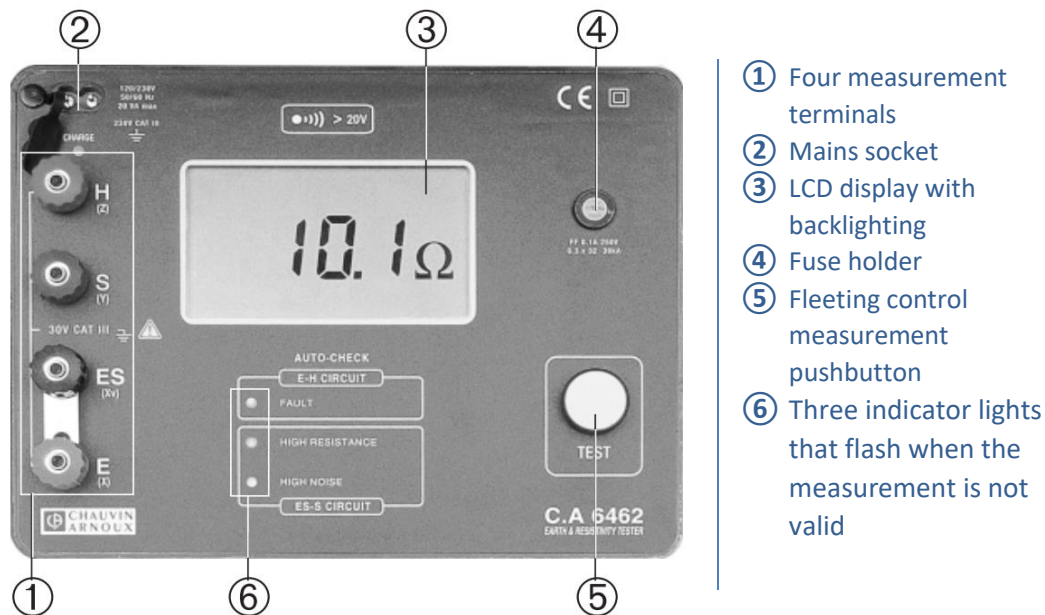


Figure 69 Clear view of interface and classification of each button/screw terminal (C.A 6460 & C.A 6462 User's manual, 2018)

The typical measuring process is shown in the flow chart below:

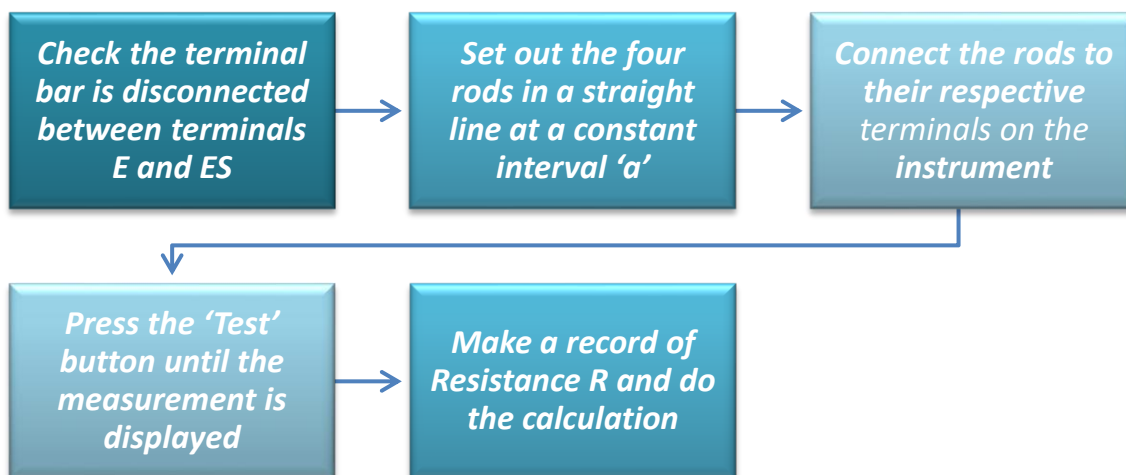


Figure 70 Measuring process of using C.A.6460

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Appendix V : Comparison between Arduino Uno & Arduino Mega 2560



Figure 71 Arduino Mega 2560 (ArduinoStore, 2021)



Figure 72 Arduino Uno Rev3 (ArduinoStore, 2021)

Arduino is a programmable single chip microcomputer circuit board (commonly known as Arduino development board) born in Italy in 2005. It has a history of more than 10 years. Arduino is different from ordinary single-chip microcomputer development board. On the basis of single-chip microcomputer, it adds electronic components that enable it to adapt to most operating conditions, such as capacitance, resistance, crystal oscillator, transistor, etc., so that it can work directly, adapt to a wide voltage, lead to a simple L/O interface, and facilitate the use of DuPont line rapid experiment and supporting expansion board.

Arduino development board can be regarded as a relatively finished MCU with simple I/O interface panel. It has the functions of MCU core programming, data processing, data storage, timer, serial and bus communication, pulse width modulation signal, analog multiplexer, analog-digital converter and so on. Therefore, I/O can be freely controlled by programming to realize electrical signal control, acquisition and electronic communication. Therefore, the learning of electronic circuit knowledge can put aside some boring and accurate circuit design, so that this part of the content can be idealized instead.

In general, the specific features of Arduino are as follows:

- be able to carry out rapid and efficient development;
- rich development resources;
- after the development board is connected to the upper computer, it can directly update the program, communication or interaction;
- the development board adapts to the power supply width;
- the development board is small and easy to transplant.

For coding, there is corresponding specific code environment software for Arduino products—Arduino IDE (as shown below). Arduino IDE has user-friendly interaction interface and its rich library, which is open-source and all Arduino IDE coder has access to that. It is very convenient to use this software to code for Arduino boards. Also, fresh men would find it easy to get used to this coding software comparing to many others.

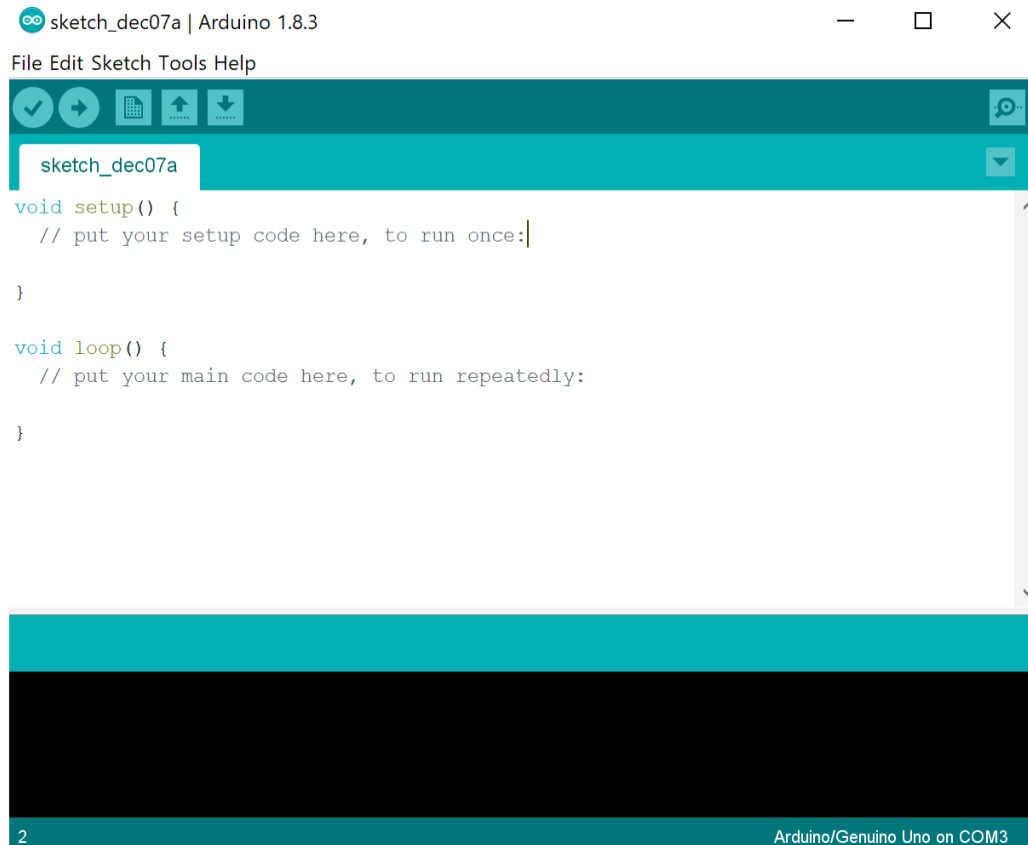


Figure 73 Arduino IDE interface

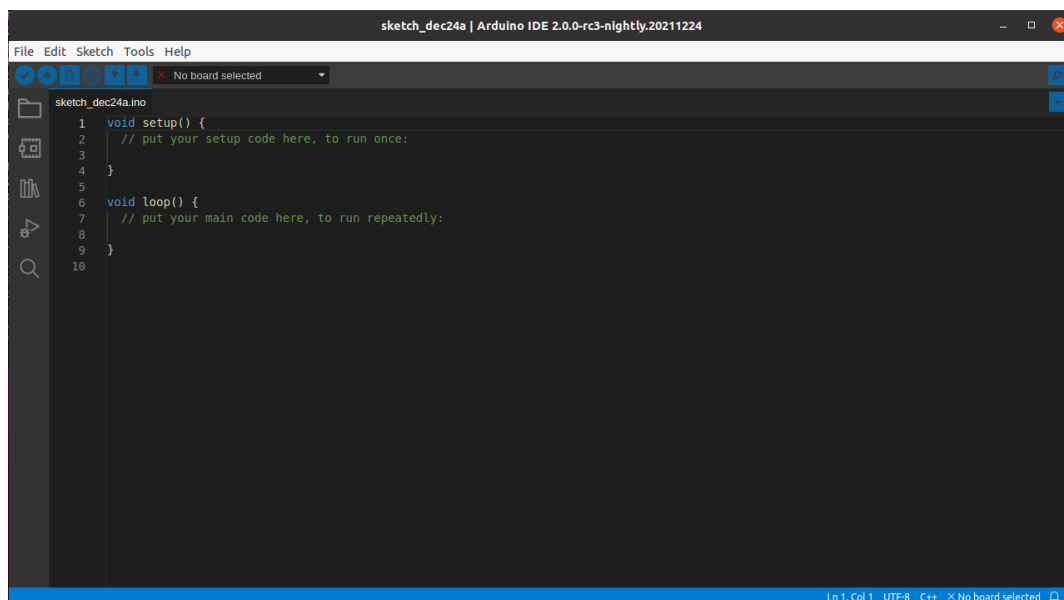



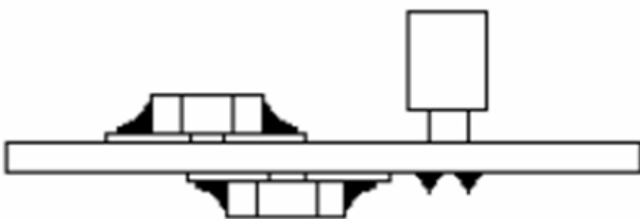



Figure 74 Arduino IDE 2.0 interface (Javaid, 2022)

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Appendix VI: Printed Circuit Board (PCB) assembly type and cost influencing factors

Table 12 Main PCB assembly types

Assembly type	Diagram	General assembly process
1. Single surface full SMD		Solder paste printed on one side, reflow solder after mounting
2. Double surfaces full SMD		A and B surfaces printing solder paste and reflow solder or B surface wave solder
3. Single surface mix assembly		A and B surfaces printing solder paste. Reflow solder SMD and wave solder through-hole components
4. Surface A mix assembly and surface B SMD		A surface printing solder paste, reflow soldering B surface glue dispensing to fix SMD and then assembly through-hole components, wave solder THD and SMD on the surface B.
5. Surface A through-hole and surface B SMD		B surface glue dispensing to fix SMD and then assembly through-hole components, wave solder THD and SMD on the surface B.

There are many factors that need to be considered in PCB price, such as size, quantity, board layers, board thickness, color, line width, line spacing and so on. Also, applying Surface Mounted Technology (SMT) in PCB or not plays a big role in the final price calculation. If choose to use SMT, the number of components to be mounted matter as well.

The several factors influence the cost of one PCB are listed and explained in detail below (SVTRONICS, INC. Chris D, 2020):

PCB Size and the Number of Layers

- PCBs are made out of different materials like fiberglass, polymer inks, and solder. These materials can affect the way the board reacts to heat.

Type of PCB Material

- PCBs that run high-tech electronics tend to have several layers.
- When boards are bigger, they cost more than the smaller ones. The space that the components consume increases the cost of the PCBs.

Size of Board Holes

- When boards are bigger, they cost more than the smaller ones. The space that the components consume increases the cost of the PCBs. The price increases not just because the PCBs are bigger; this is because bigger boards and boards with several layers take more time to manufacture.

Cost of Labor

- Producing PCBs is a costly endeavor because skilled professionals do the work. They need to use automated machinery that is designed specifically for PCB manufacturing. Labor costs affect the price of producing a PCB.

Quantity of PCB in the Order

- PCBs often have a lower cost if they are ordered in bulk. Once a prototype is made, it is easy to duplicate them. Building the prototype is expensive, which is why small orders cost more per piece than a bulk order does. Many companies will discount bulk orders, so do not be afraid to request a lower price.

Expected Turnaround Time

- Some manufacturers are building PCBs with a quick, turn-key turn around time. When manufacturers are asked to produce PCBs quickly, they will charge more money. Often, manufacturers have to put other orders on hold to get a quick turnaround on another order. The increased price will cover the expense of putting other orders on hold.

Packaging Costs

- Shipping fragile electronics components can be expensive. Some PCBs need to be packaged with their electrical parts connected, and these types of projects often need delicate packaging materials, which adds to the cost of the manufacturing.

In general, the cost to produce a PCB will cost between \$10 and \$50 per board. The actual price will be determined by the manufacturer and could be higher or lower based on the components, size, and type of material used. Sometimes, the smaller boards cost more because they require more labor hours to get components working properly, especially if the board has to power something like a smartphone or other small, complicated device.

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Appendix VII: Labor issue

VI. I Labor costs (in the Netherlands)

The cost of labor is the sum of all wages paid to employees, as well as the cost of employee benefits and payroll taxes paid by an employer. The cost of labor is divided into direct and indirect (overhead) costs. Direct costs include wages for the employees that produce a product, including those on an assembly line, while indirect costs are associated with auxiliary labor, such as employees who maintain factory equipment (Brock, 2020).

To do a comprehensive project, no matter what type of project it is, besides the component prices it is also necessary to consider the cost of labor. This kind of costs varies depending on the nature of the project, such as project field, implementing place, etc. The final prototype is merely for the project, not for large-scale commercial use because this is an educational project, the specific labor cost is quite low here.

KEY TAKEAWAYS

- Labor costs fall into two broad categories, direct (production) and indirect (non-production) labor costs.
- Direct costs refer to the wages of employees who produce products (including workers on the assembly line), while indirect costs are related to supporting labor, such as employees who maintain plant equipment.
- Improper allocation or evaluation of labor costs may cause the price of goods or services to deviate from their actual cost and damage profits.

Working hours in the Netherlands

The standard work week in the Netherlands is 38 hours. Most full-time jobs in the Netherlands are 36-40 hours per week, or 7-8 hours per day, 5 days per week.

Some companies work a 40-hour week instead of the standard 38 hours, in which case the longer the employee works, the higher the pay. Another way to compensate for the increased working week is to increase annual leave (sometimes to about 12 days).

In the Netherlands, the lunch break is usually 30 minutes and is not paid.

As shown in Figure 75 below, it provides the most recent statistics on labor costs per hour in the European Union (EU).

The average hourly labor expenses in the European Union (EU) and the euro region were expected to be €29.1 and €32.8 respectively in 2021. However, this average conceals significant disparities across EU Member States, with Bulgaria (€7.0) and Romania (€8.5) having the lowest hourly labor expenses and Denmark (€46.9), Luxembourg (€43.0), and Belgium (€41.6) having the highest.

It is clear that the average labor cost per hour in the Netherlands is about 38 euros, which is almost 9 euros higher than that in the EU. This means that, to some extents, labor costs in the European region are quite high and therefore labor costs need to be kept in mind when designing systems, sub-systems and corresponding components in this project.

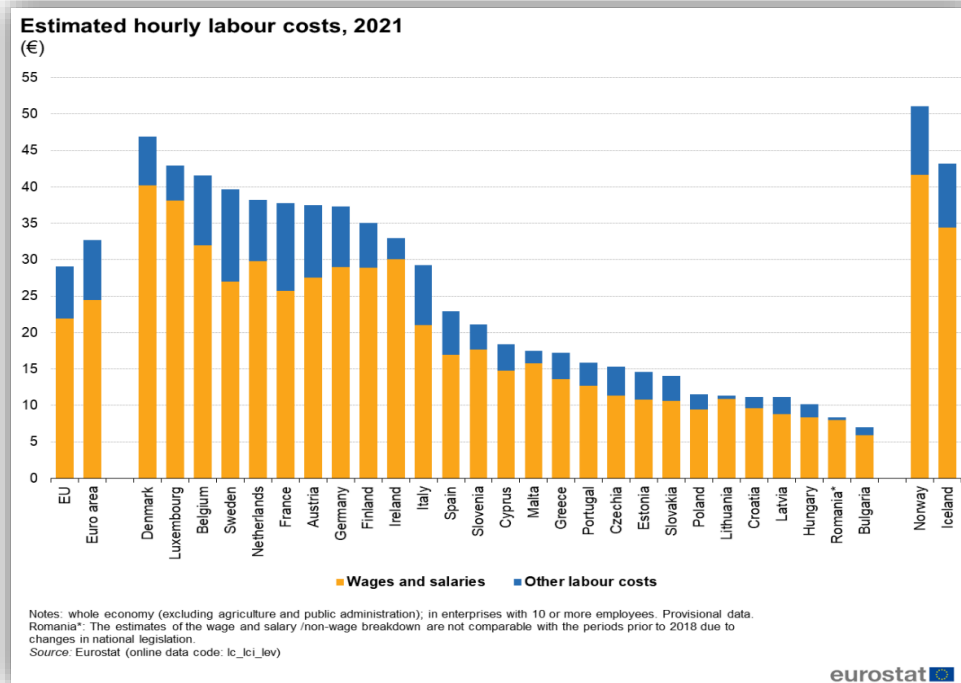


Figure 75 Estimated hourly labor costs in European region, 2021 (eurostat, 2021)

VI. II Measures to reduce labor


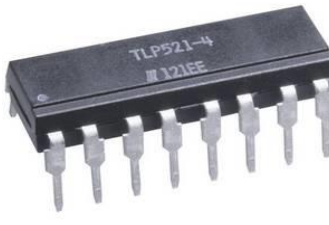


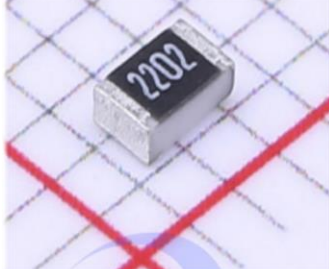
Labor is one of the crucial factors that influence many aspects of one project, so it is significant to consider reducing labor according to project management methodology. The ways to decrease this kind of cost vary in different projects. Now provide several methods specifically for this project as below:

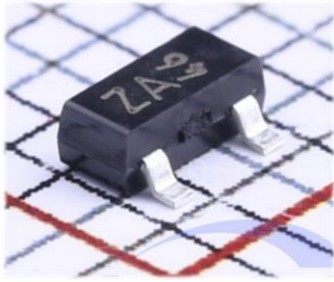
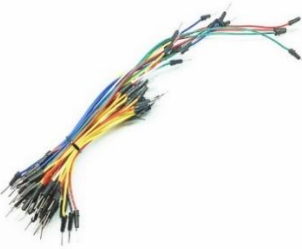

1. Consider more possibilities of microcontroller use, take as smaller and lower-cost microcontroller that can be compatible for the realization of function required in the project as possible. For example, in this project, it is wise to consider simplifying the circuit design including signal source circuit, measuring module, etc. If Arduino Nano is already enough to support all functions, then replace Uno board with Nano board to reduce labor.
2. Increase Efficiency. Having more progress within the same time can decrease labor in the project to a great degree. Time is money, especially in an internship thesis project, so the time saved can be exploited at other aspects of the project.
3. Optimize the circuit scheme, use as few components as possible to achieve more functions and simplify the circuit layout, for instance, If the original chip board is a two-layer chip board, all components are integrated into one board through reasonable distribution of components and circuits, which saves space and cost.
4. There are many ready-made components in the company workshop, therefore, when designing system and subsystems, it is best to give priority to those existing electronics boards and components in the company storage. In this case, the cost of project can be saved to a great degree and this also avoids waste and repeat purchases.
5. When purchasing electronics component online, chose provider as nearby as possible to reduce the deliver cost and period.

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Appendix VII: Component list

Table 13 List of components

Component	Description	Amount	Price/each	Link
	ADS1115 is a kind of analog-to-digital electronics chip. The precision is 16-bit at 860 samples/second. The realization of data transmission is via I2C. The chip boasts two operation modes. Generally speaking, the performance of this chip is relatively excellent comparing to the similar type electronics.	1	€ 7,39 (The company provides)	https://vicedeal.com/products/ads1115-ultra-kleine-16-bit-precisie-analoog-digitale-converter-adc-4-kanaals-development-board-module?gclid=CjwKCAjwkMeUBhBuEiwA4hpqEAtZBTpcjU1vVvwsRdMo_gO5K22OPd3cA6w_jlmoPzExJyRI0uEXghoCLqcQAvD_BwE&variant=UHJvZHVjdFZhcmlihnQ6MjY1ODEwNDMw
	The TLP521-4 is a 16-pin DIP through-hole optically linked isolator. Infrared light emitting diodes and NPN silicon photo transistors make up the isolator. This isolator is commonly used in computer terminals, industrial system controllers, and signal transfer between systems with various potentials and impedances.	23	€ 1,04	https://nl.farnell.com/isocom/tlp521-4/optocoupler-dip-16-quad-tr-o-p/dp/1683372?ost=tlp521-4
	Arduino Mega is an Arduino development board based on ATmega2560. It has 54 digital input / output pins (15 of which can be used for PWM output), 16 analog input pins, 4 UART interfaces, a 16 MHz crystal oscillator, a USB interface, a DC interface, an ICSP interface, and a reset button.	1	€ 22,24 (there is ready-made boards in the company workshop)	https://www.bol.com/nl/nl/p/otronic-mega-2560-r3/9300000024846565/?Referre r=ADVNLG00002013-G-138543199184-S-1076001530805-9300000024846565&gclid=CjwKCAjwkMeUBhBuEiwA4hpqEP TwNPWKGPkH9jYLVMO5HXF0 bxNDbm5rNU8iM024GKmXtJfc vp10vxoC3cYQAvD_BwE
	2N3906, a kind of PNP transistor, is mainly used to amplify electrical signals and is widely used in various amplification circuits. This transistor can be used to drive any load below 200mA, such as relay, led, high-power transistor, etc. Since the emitter base voltage of the transistor is 5V, it can also be used for the output of the microcontroller	3	€ 0,164	https://nl.farnell.com/multicomp/2n3906/transistor-45v-200ma-pnp-to-92/dp/1574372?st=2n3906
	SMD resistor, there are several different resistances used.	148	€ 0,002 (Integrated into PCB)	https://cart.jlpcb.com/smtQuote?pcbFileNo=ee0f71cc4f5548eeae6f3563f61996a8

	SMD transistor, the chip fixed type of 2N3906. Description: 40V 350mW 200mA 100@10mA,1V 250MHz 400mV@50mA,5mA PNP +150°C @(Tj) SOT-23(SOT-23-3) Bipolar Transistors - BJT ROHS	23	€ 0,014 (Integrated into PCB)	https://cart.jlpcb.com/smtQuote?pcbFileNo=ee0f71cc4f5548eeae6f3563f61996a8
	Jumper cables is used to connect each electronic component and make them compose the complete closed loop circuit.	Several	Less than € 10,00 in total (The company provides)	https://www.otronic.nl/a-60558956/draden-en-kabels/dupont-jumper-kabels-40-stuks-male-female-10cm-draadbruggen-voor-breadboard/?gclid=CjwKCAjwkMeUBhBuEiwA4hpqEMVBiuNTmJx5vIDTvvCoLBIHQauyxwlfjzKayeHGxek9Ea8kUS8sxRoCjEcQAvD_BwE
	The whole bread board is made of thermosetting phenolic resin. There are metal strips at the bottom of the board. Holes are punched at the corresponding positions on the board so that the elements can contact the metal strips when inserted into the holes, so as to achieve the purpose of conducting electricity.	2	€ 4,99 (The company provides)	https://www.bol.com/nl/nl/p/breadboard-experimenteerbord-400-gaats-soldeerloos-prototyping-otronic-arduino-esp32-esp866-wemos/9300000005200215/?Referer=ADVNLGOO002013-G-138543199184-S-1075852962858-9300000005200215&gclid=CjwKCAjwkMeUBhBuEiwA4hpqELGyzmGXPHPSuJVISJgE5wMDmtKQOh4LWZsEJx-Vepske4woKk7nhoCmYoQAvD_BwE

Cost of project:

$$1,04 \times 23 + 0,164 \times 3 + 24,78 = 49.192 \text{ (€)}$$

If take the cost of components that company provides into consideration, the cost of project:

$$49.192 + 7,39 + 22,24 + 4,99 \times 2 + 10 = 98.802 \text{ (€)}$$

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PCB Price	
Engineering fee	\$4.00
Board	\$5.60
SMT Price	
Setup fee	\$8.00
Stencil	\$1.50
Panel	\$0.00
Large Size	\$0.00
Components	\$1.42
Extended components fee	\$3.00
SMT Assembly	\$1.26
Build Time	
PCB: 2-3 days	\$0.00
SMT: 3 days	
Total Price	\$24.78
Weight	513.00g

Figure 76 Price list of PCB including components assembly

Appendix VIII: Schematics and properties of core components

Analog-to-digital converter --- ADS1115

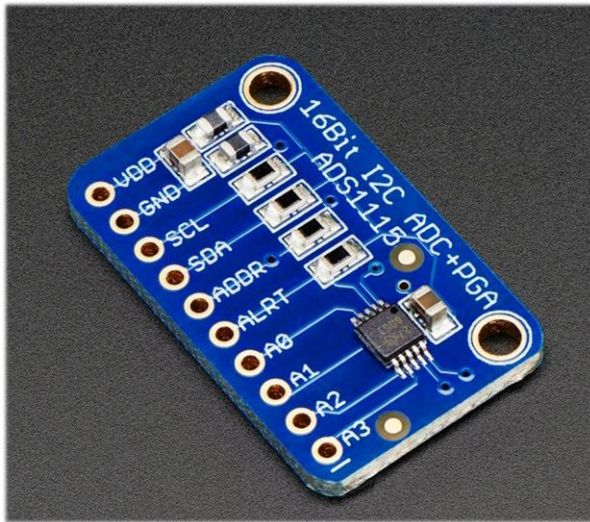


Figure 77 ADS1115 overview (adafruit store, 2022)

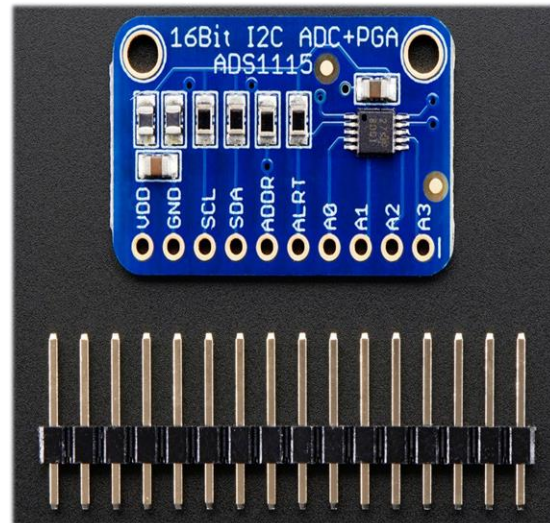


Figure 78 ADS1115 with plugs (adafruit store, 2022)

In the previous project—4 electrodes soil resistance meter design, analog-to-digital converter ADS1115 was chosen for the responsibility of detecting and measuring the differential voltage between electrodes and current through them. There was adequate research on this kind of ADC and many tests and reports about it, all of which provided the proof that this AD converter is quite capable for the soil resistance meter design project. Therefore, in 2022 project, this component will be still used in circuit design.

ADS1115 is a very excellent chip that meets relatively high requirement in electronics system design. The precision of this chip is 16-bit and its sample rate is 860 samples/second over I2C. The chip has two working modes -- single-ended input channel measurement & two differential channels measurement. As a nice bonus, it even includes a programmable gain amplifier, up to x16, to help boost up smaller single/differential signals to the full range. Besides, this AD converter can run from 2V to 5V power/logic, can measure a large range of signals and its super easy to use. In general, it is a great general purpose 16-bit converter (adafruit store, 2022).

Technical Details

- Supply Range: 2.0V — 5.5V
- Low Current consumption: 150 μ A (in Continuous Mode); Auto Shut-Down (In Single-Shot Mode)
- Programmable Sample Rate: 8 — 860SPS
- Internal Low-drift voltage reference/ Oscillator/ PGA
- I2C interface: Pin-Selectable Addresses
- Four single-ended or two differential inputs
- Comparator is programmable
- Addresses of board: 0x48-0x4B (I2C, 7-bit)

Optocoupler --- TLP521-4

Tlp521-4 is a controllable optical coupling device, which is widely used in computer terminals, thyristor system settings, measuring instruments, photocopiers, automatic ticket sales, household appliances, such as electric fans, heaters, etc. The signal output between circuits makes the front end completely isolated from the load. The purpose is to enhance the safety of the circuit, reduce the interference of voltage and simplify the design of the circuit.

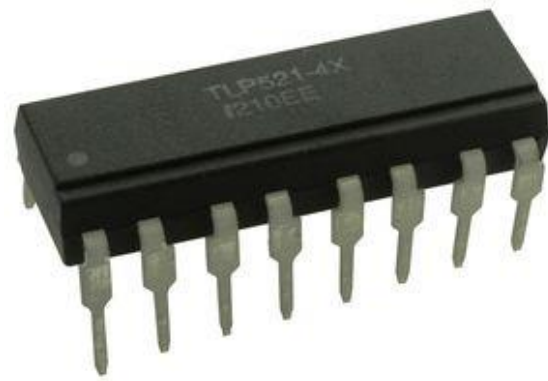
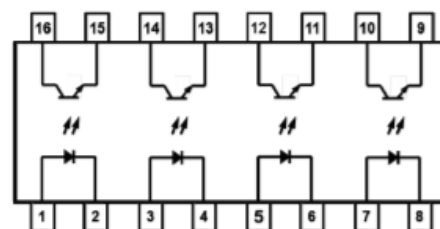


Figure 79 TLP521-4 overview (ISOCOM, 2022)

Technical Details

- Collector--Emitter Voltage (Max): 55V
- Collector Current: 50mA.
- Working temperature (Max): 100°C
- Working temperature (Min): -55°C
- Current transfer ratio (Max): 600%
- Current transfer ratio (Max): 50%
- Isolation voltage (Min): 2500 Vrms
- Similar with TLP521-2 & TLP521
- AD/DC input modes
- 4 independent optocoupler units

TLP521-4



1, 3, 5, 7 Anode
2, 4, 6, 8 Cathode
9, 11, 13, 15 Emitter
10, 12, 14, 16 Collector

Figure 80 Pin configuration of TLP521-4 (ISOCOM COMPONENTS, 2020)

TLP521-4

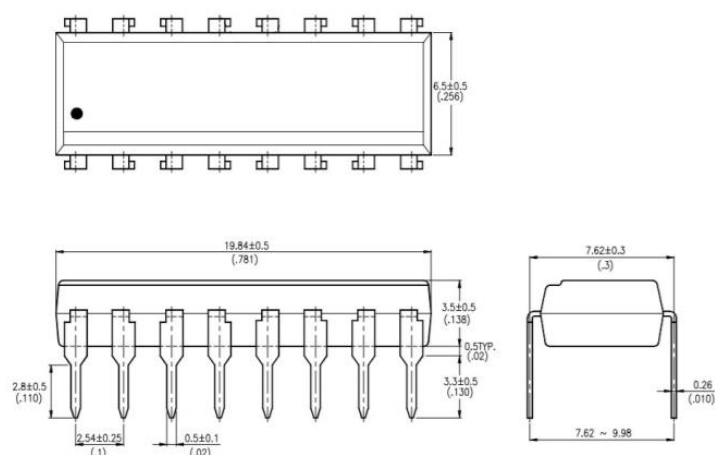


Figure 81 Dimensional design drawing of TLP521-4 (ISOCOM COMPONENTS, 2020)

Appendix X: Switch sequence determination and truth table

The switch system would choose 4 – electrode set (firstly electrode 1,2,3,4) once and after the first measurement process, orderly choose another 4-electrode set (electrode 2,3,4,5) and repeat the measurement process then move to next set until the last electrode combination (electrode 23,24,25,26). Therefore, there are 23 measurements during one measuring process. However, when measuring in real soil, the conditions would be much more complicated and the measuring mode mentioned above would cause an effect called remanent magnetization, which significantly damages to the accuracy of the data collected. To eliminate this kind of side effect, the switch order of electrodes is made some adjustments. Still start from electrode 1,2,3,4 but after moving to step 2, electrode 2,3,4,5 will not be chosen, instead, electrode 5,6,7,8 would be chosen and then electrode 9,10,11,12 and so on. In this case, there are only 6 measurements in one cycle, so 4 cycles are required to realize the measurement of 23 possibilities. The brief switch process is displayed below:

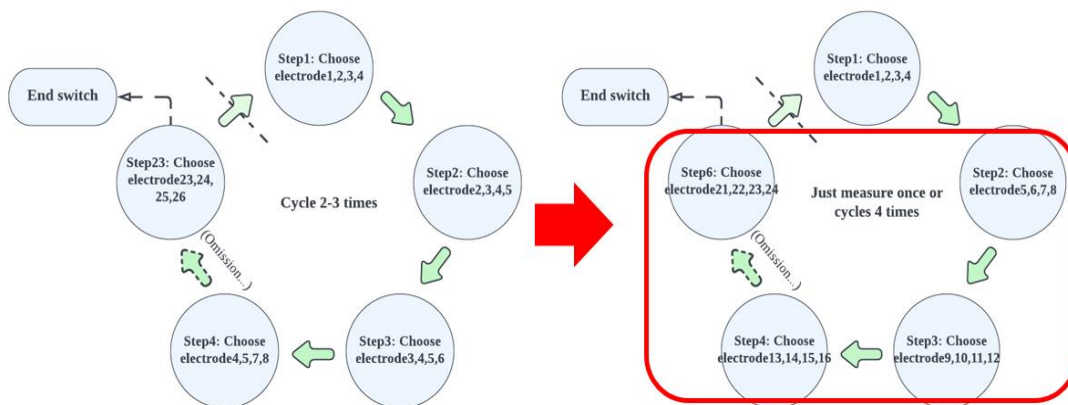


Figure 82 The adjustment of switch sequence

Finally, optocoupler TLP521-4 device is determined to use for this project as core component. Optocoupler is a kind of contactless switch, whose main characteristics are that there are no movable contact parts, there is no arc or spark when switching on or off, the action is rapid, the service life is long, and the reliability is high. The usage range is quite wide of this kind of device and it is also suitable for some special environments such as fire prevention, explosion-proof and moisture-proof. Relatively speaking, contactless switch is more extensive in safety and use than contact switch.

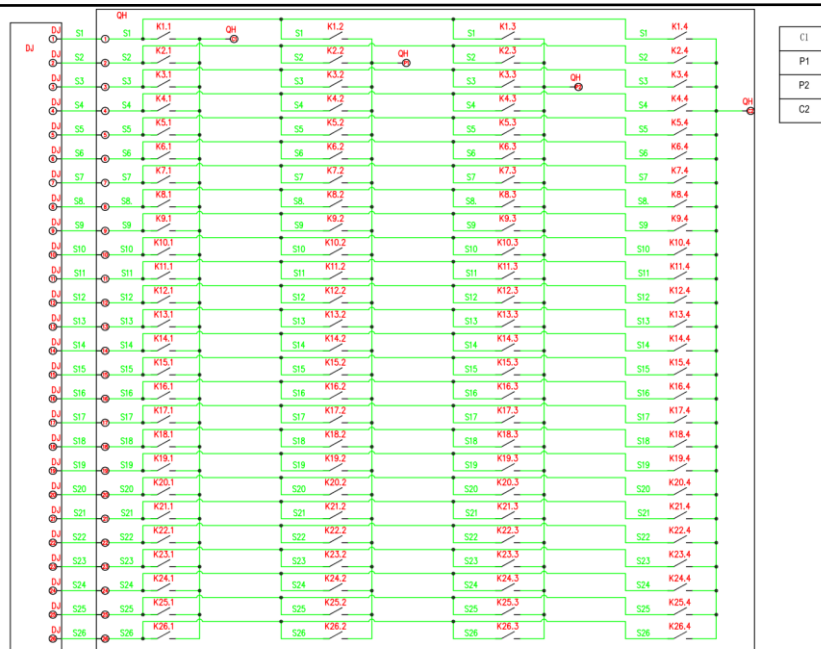


Figure 83 Schematic circuit design of all possibilities

As shown in figure above, by using these so many switches, it is theoretically possible to realize every combination of 4-electrode set in one measurement. But as Wenner method, which is a method requires all distances of electrode chosen are same, it is not needed to use all these switches. Instead, just some of them are truly necessary.

For clearer demonstration, a switch sub-system truth table was made (shown as below). C1, P1, P2 and C2 represent the four terminals in measuring sub-system. As mentioned earlier, it is manifest from this figure that 4 groups (cycles) could complete the assignment to switch and measure electrodes from number1, 2, 3, 4 to number23, 24, 25, 26, which are 23 possibilities totally.

group1	C1	P1	P2	C2	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	K13	K14	K15	K16	K17	K18	K19	K20	K21	K22	K23	K24
Q11	1	2	3	4	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q12	5	6	7	8	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q13	9	10	11	12	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Q14	13	14	15	16	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0
Q15	17	18	19	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
Q16	21	22	23	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
group2	C1	P1	P2	C2	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20	L21	L22	L23	L24
Q21	2	3	4	5	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q22	6	7	8	9	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q23	10	11	12	13	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Q24	14	15	16	17	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0
Q25	18	19	20	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
Q26	22	23	24	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
group3	C1	P1	P2	C2	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24
Q31	3	4	5	6	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q32	7	8	9	10	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q33	11	12	13	14	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Q34	15	16	17	18	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0
Q35	19	20	21	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
Q36	23	24	25	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
group4	C1	P1	P2	C2	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19	N20	N21	N22	N23	N24
Q41	4	5	6	7	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q42	8	9	10	11	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q43	12	13	14	15	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Q44	16	17	18	19	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0
Q45	20	21	22	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
Q46	24	25	26	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1

Figure 84 Truth table of the switch-measuring process

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Appendix XI: Printed Circuit Board (PCB) document file and corresponding circuit schematic

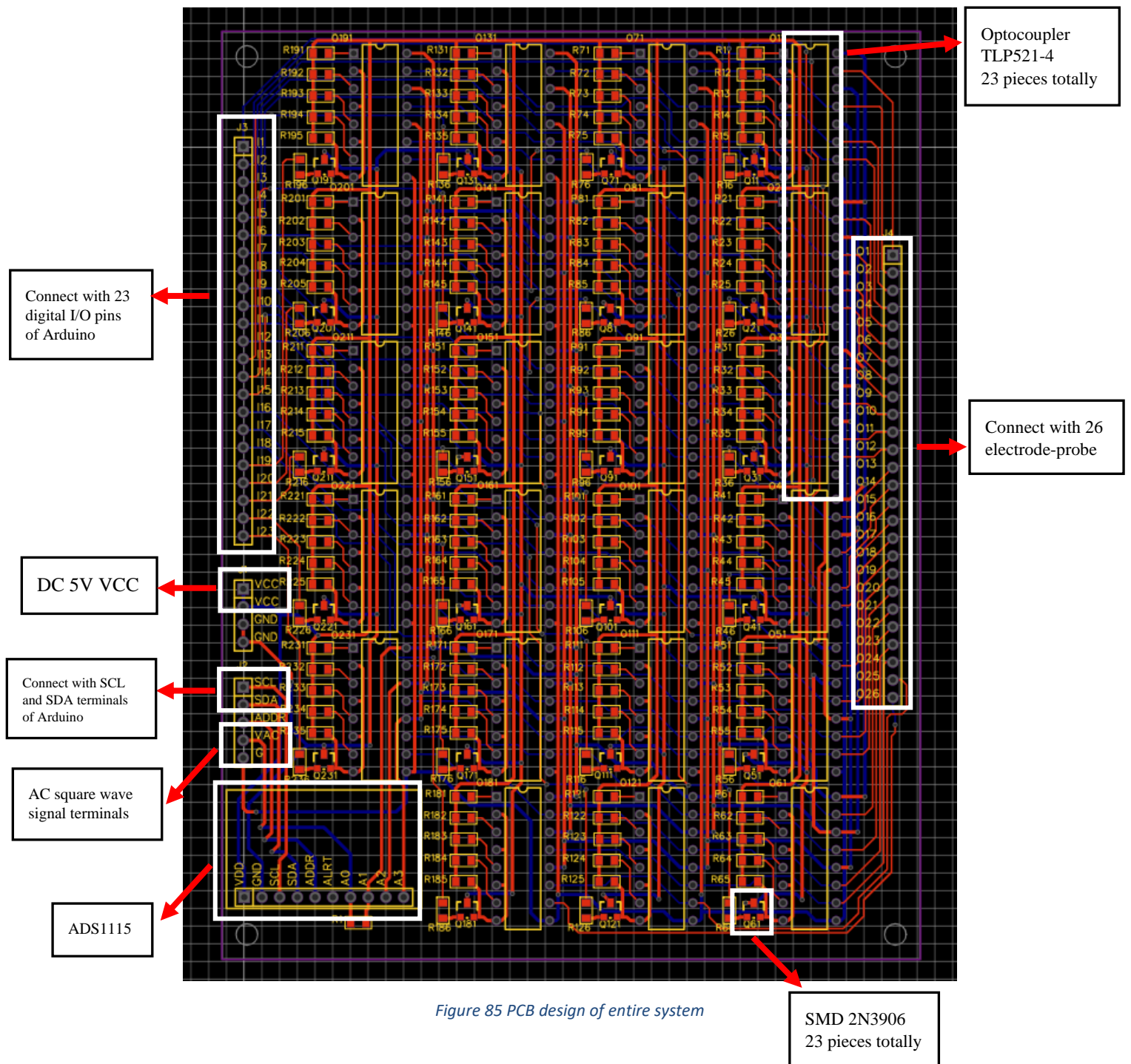


Figure 85 PCB design of entire system

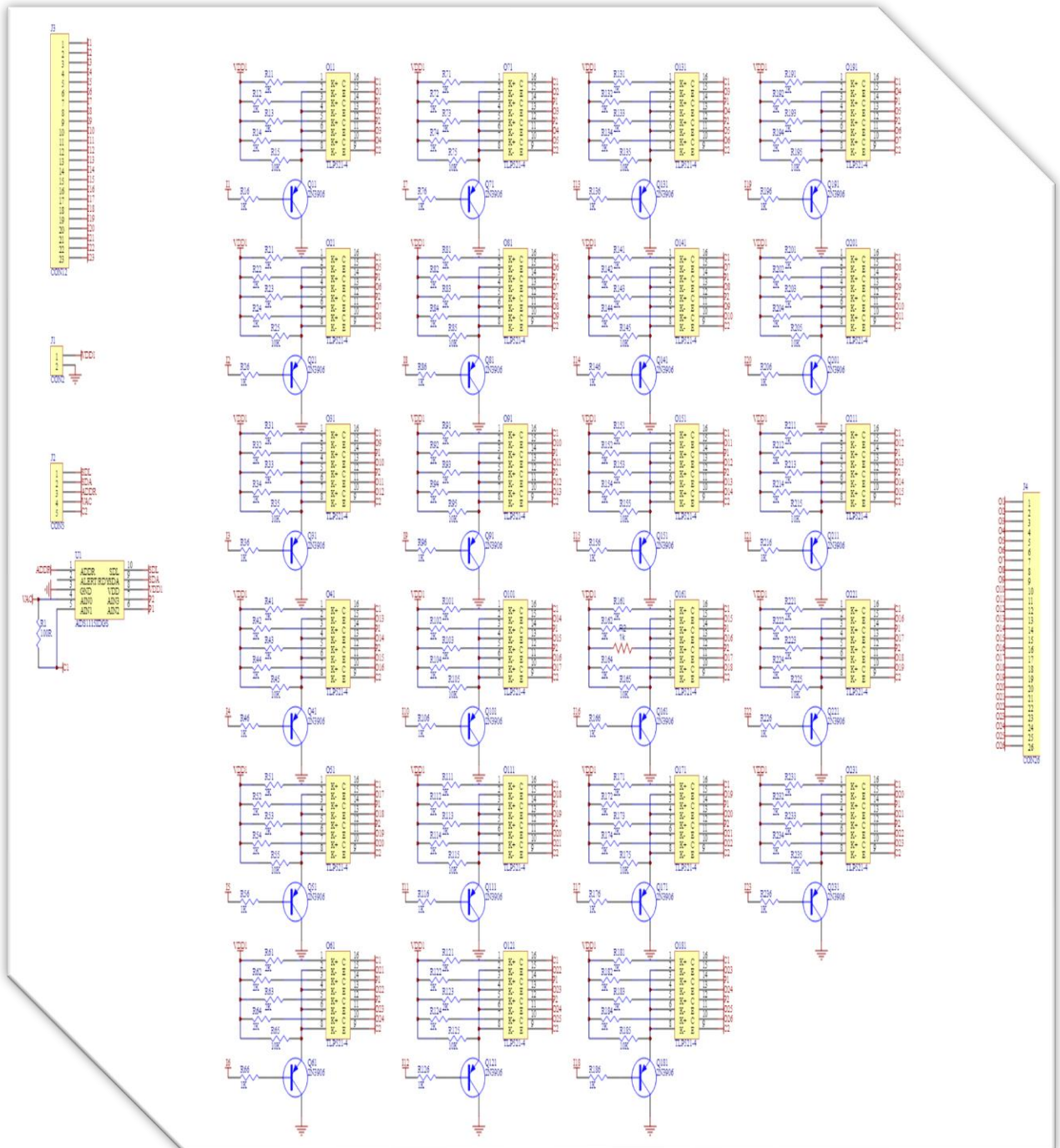


Figure 86 Circuit schematic of PCB

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Appendix XII: Test plans and test results

Demonstration test plan:

Aim

This demo test plan is aimed to simulate the operation of the soil resistivity measurement and confirm that the system has the capability to switch within 4-electrode sets to measure according to the specific coded order from Arduino microcontroller. Finally, prove that this system is feasible at the level of proof of concept.

Variables:

Table 14 Variables in Demonstration test

Nr.	Property	Vary/Measure	Unit
1	Power for whole system	Vary	W/ V
2	Soil (resistance)	Measure	Ω
3	Frequency	Vary	Hz
4	Differential voltage	Measure	V
5	Chosen electrodes	Vary	\
6	Output digital signal	Measure	\
7	Error	Measure	\
8	Stability	Measure	\

Test tools (devices):

- Integrated system prototype with some rest jumper cables
- Laptop
 - Excel: data display and analysis
 - Arduino IDE
- Several resistors representing the underground soil resistors. (Or Saltwatcher2.0 device located at HZ sea lab)
- Multimeter and oscilloscope

Method:

1. Provide power to the Automated Electrode-switch Salt Watcher system (using laptop)
2. Connect the Automated Electrode-switch Salt Watcher system with the simulation resistors to be measured.
3. Conduct demonstration test.
4. Execute the measurement process several times depending on the specific requirements on site.
5. Read the test results from the display (screen or Arduino IDE serial monitor).
6. Repeat the demonstration test and compare the data collected within these two experiments.
7. Disconnect the power of the Salt Watcher and the wiring, organize all the stuff used in this test.

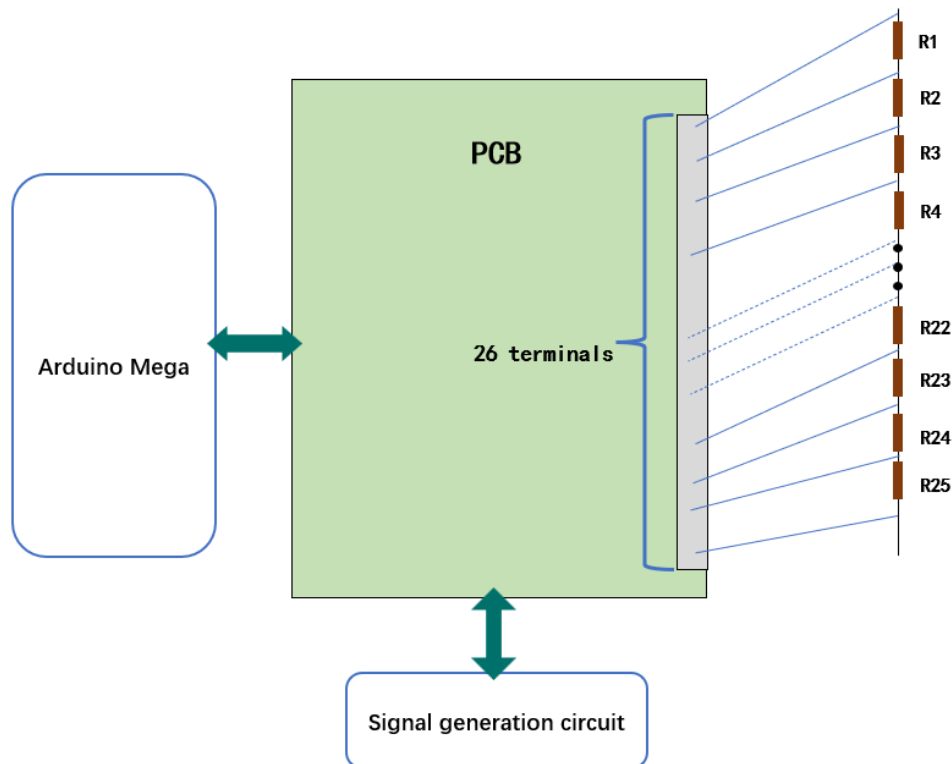


Figure 87 Demonstration test sketch

Expected result:

The expected result is that this Automated Electrode-switch Salt Watcher system has the ability to switch electrode sets (replace with 25 resistors) sequentially and moreover, measure the values of current and voltage of the chosen electrodes and show the results to the users via serial monitor in Arduino IDE or display screen. In addition, the accuracy of the resistance measured is supposed to meet the expectation.

Automated electrode-switch salt watcher system test plan (at HZ SEA Lab):

Aim:

The aim of this automated electrode-switch salt watcher system test at HZ sea lab is to test whether this system is able to detect the resistance between electrodes in practical use and at the same time, meet the requirement of value accuracy to some degrees.

Hypothesis:

After manually connecting the PCB terminals and terminals of Salt Watcher Prototype2.0, the resistance of the 4-electrode can be measured and displayed in Arduino IDE. Besides, the error between the values derived by this system and the values measured by professional measuring device C.A 6460 is under 10%. If meet both requirements mentioned above, the system is judged to pass the test.

Variables:

Table 15 Variables in Automated electrode-switch salt watcher system test

Nr.	Property	Vary/Measure	Value	Unit
1	Power for whole system	Vary	5.0	V
2	Resistance	Measure	\	Ω
3	Frequency of AC square wave	Vary	800	Hz
4	Output measuring voltage	Measure	2400-2600	mV
5	Differential voltage of electrodes	Measure	10-200	mV
6	Output digital signal from Arduino board	Vary	\	\

Testing Tools:

Table 16 Testing tools in Automated electrode-switch salt watcher system test

Nr.	Item	Demands
1	Laptop	\
2	Connecting cable (Micro-USB)	\
3	Mobile phone	Photography and video
4	Jumper cables	\
5	Breadboard	\
6	C.A 6460	As reference
7	Arduino Mega board	\
8	Automated electrode-switch salt watcher system PCB	\

Method

1. Connect voltage divider resistors which are used to configure AC square waves with Arduino board.
2. Connect Arduino board to PCB and connect Arduino board with laptop, enabling Arduino board as power supply.
3. Connect one combination of electrodes to the PCB.
4. Upload code into Arduino Uno board and open IDE serial monitor.
5. Observe and record the results displayed.
6. Repeat step 3 to 5 until finish the measurement of 7 combinations of as required from Wenner configuration manual.
7. Use C.A 6460 to measure that 7 groups electrode sets and record test results.
8. Compare the values derived by the system prototype with those derived by C.A 6460.
9. Disconnect all wires and organize devices and instruments and components.

Expected results:

For each 4-electrode set measurement, the resistance can be displayed in Arduino IDE successfully. In addition, the values detected by the Automated electrode-switch salt watcher system PCB is relatively equal to those values measured by C.A 6460, of which the errors are all under 10%.

cm	minifilter	elektroden	Wenner configuratie						
	plaatsing		50	40	30	20	10	20B	10B
235									
230									
225									
220									
215									
210									
205									
200									
195									
190	16	16							
185									
180	15	16							
175									
170	14								
165									
160	13	17							
155									
150	12								
145		16							
140	11	15							
135		14							
130	10	13							
125		12							
120	9	11							
115									
110	8	10							
105		9							
100	7	8							
95		7							
90	6	6							
85		5							
80	5								
75									
70	4	4							
65									
60	3	3							
55									
50	2	2							
45									
40	1	1							
35									
30									
25									
20									
15									
10	1								








Figure 88 Wenner configurations



Figure 89 Photo of set-up of the on-site test

Test results

Table 17 Comparison between the measurement of system prototype and C.A 6460

Nr.	Wenner Configuration	Measurement of system prototype	Measurement of C.A 6460
1	50	Group 1: RefDifferential: 740(139.12mV) Differential: -145(-27.26mV) Resistance= 19.63	
2	40	Group 1: RefDifferential: 651(122.39mV) Differential: -109(-20.49mV) Resistance= 16.78	
3	30	Group 1: RefDifferential: 621(116.75mV) Differential: 493(92.68mV) Resistance= 79.55	
4	20	Group 1: RefDifferential: 532(100.02mV) Differential: 143(26.88mV) Resistance= 26.93	
5	10	Group 1: RefDifferential: 501(94.19mV) Differential: 220(41.36mV) Resistance= 44.00	
6	20B	Group 1: RefDifferential: 508(95.50mV) Differential: 333(62.60mV) Resistance= 65.68	
7	10B	Group 1: RefDifferential: 668(125.58mV) Differential: -119(-22.37mV) Resistance= 17.85	

As the data shown in the table, some test results (group Nr. 1,2,4,5,7) are relatively accurate but there are still several wrong measurements (group Nr.3 and Nr.6). Now organize the data into table and calculate the errors, as shown below.

Table 18 Error calculation

Nr.	Measurement (Ω)	Actual resistance(Ω)	Error
1	19.63	18.48	6.22%
2	16.78	16.74	0.24%
3	79.55	21.6	268.29%
4	26.93	28	3.82%
5	44	49.4	10.93%
6	65.68	15.26	330.41%
7	17.85	17.09	4.45%

Test code:

The same as the code of automated electrode-switch salt watcher system.

Conclusion:

It can be concluded from the test results that in real conditions, the automated salt watcher system can still detect the resistance between electrodes. However, the operation of detection is not stable, leading to the measurement fluctuating significantly and some test results were even not correct due to the influences of some practical factors. The errors of more than half of the test data are less than 10%, and therefore, the system has passed the test to a certain extent. The cause of the wrong data is still uncertain, which requires further follow-up research.

Automated electrode-switch salt watcher system test plan (in lab conditions):

Aim:

The aim of the automated electrode-switch salt watcher system test is to test whether the system integrated into a PCB is able to stably detect the value of the voltage and current to be measured and switch the electrode set automatically successfully.

Hypothesis:

When the PCB is supplied with external AC square wave signal source, the system works normally and the values measured keep stable relatively. Also, the resistors to be measured could be switched automatically within 23 groups in total. If meet both requirements mentioned above, the system is judged to pass the test.

Variables:

Table 19 Variables in Automated electrode-switch salt watcher system test

Nr.	Property	Vary/Measure	Value	Unit
1	Power for whole system	Vary	5.0	V
2	Resistance	Measure	270, 510, 2000, etc	Ω
3	Frequency of AC square waves	Vary	800Hz	Hz
4	Amplitude of AC square waves	Vary	700-800	mV
5	Output digital signal from Arduino board	Vary	\	\

Testing Tools:

Table 20 Testing tools in Automated electrode-switch salt watcher system test

Nr.	Item	Demands
1	Laptop	\
2	Connecting cable (USB Micro B)	\
3	Oscilloscope (DSO5202P)	\
4	Mobile phone	Photography and video
5	Jumper cables	\
6	Breadboard	\
7	Multimeter	\
8	Arduino Mega board	\
9	Automated electrode-switch salt watcher system PCB	\

Method:

1. Layout voltage divider resistors of signal-generation sub-system reasonably on breadboard.
2. Connect Arduino Uno 5V power to PCB as power source of the system excluding the voltage & current measuring sub-system.
3. Connect signal generation sub-system with PCB, using AC square waves as power source of voltage & current measuring sub-system.
4. Connect Arduino Uno board with laptop, enabling Arduino board as power supply.
5. Upload code into Arduino Uno board and open IDE serial monitor.
6. Observe and record 23 values measured of the system one by one in one measurement.
7. Repeat step 6 three times to get 3 groups test results.
8. Use multimeter to measure the resistances of the simulation resistors.
9. Disconnect all wires and organize devices and instruments and components.
10. Compare the data measured by Automated electrode-switch salt watcher system and the data collected by multimeter.

Expected results:

Both switch function and measuring function operate normally. Every same time interval, the resistance is measured and displayed in the Arduino IDE serial monitor. The value measured cycled from group 1 to group 23 automatically, which means there are 23 values derived in one measurement process.

Test results

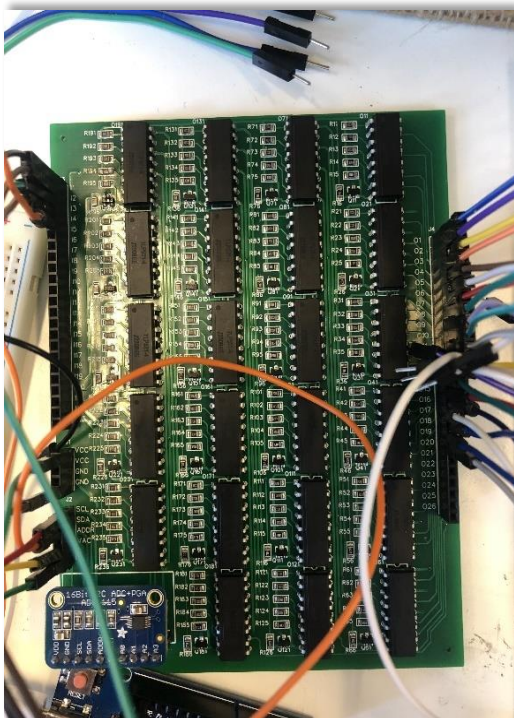


Figure 90 PCB overview

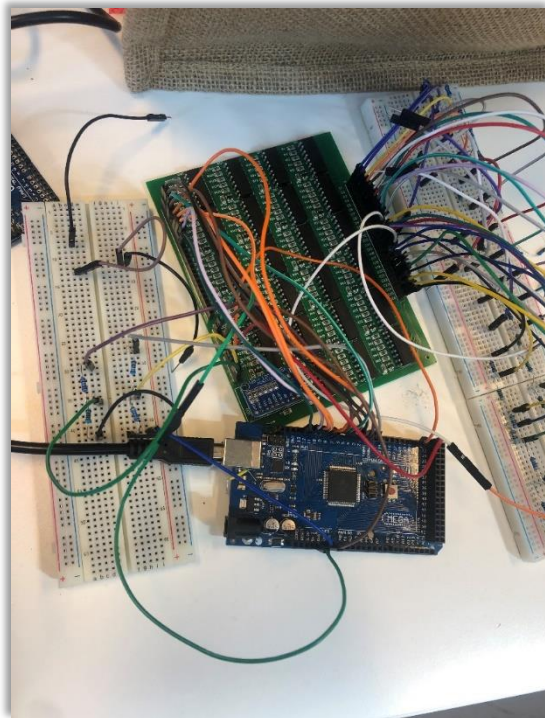


Figure 91 Setup of Automated electrode-switch salt watcher system test

Table 21 Test results in Automated electrode-switch salt watcher system test

Nr.	Test1 (Ω)	Test2 (Ω)	Test3 (Ω)	Test using Multimeter (Ω)
1	2042.73	2062.59	2034.27	2046
2	330.97	330.45	329.65	330
3	678.37	675.46	674.3	678
4	20.04	20.18	20.26	20.2
5	2203.78	2191.87	2184.39	2212
6	2209.26	2221.10	2254.51	2221
7	2035.64	2044.62	2029.05	2051
8	996.06	994.72	986.95	998
9	216.17	220.38	217.81	219
10	100.66	98.40	101.13	100.7
11	2000.21	2142.74	2078.23	2049
12	331.43	329.23	326.51	332
13	99.75	99.68	100.20	99.6
14	505.42	508.19	511.02	508
15	509.02	505.60	506.33	509
16	467.83	466.97	468.42	469
17	327.76	331.85	330.66	333
18	671.26	674.43	674.36	674
19	993.67	995.07	997.36	998
20	1001.33	998.60	1003.28	1003
21	991.22	987.45	999.05	994
22	150.30	149.81	151.57	150.9
23	4665.19	4661.53	4668.28	4690

```

975 x 1020
Group 1:
RefDifferential: 118(22.18mV)
Differential: 2429(456.65mV)
Resistance= 2062.59
Group 2:
RefDifferential: 282(53.02mV)
Differential: 930(174.84mV)
Resistance= 330.45
Group 3:
RefDifferential: 336(63.17mV)
Differential: 2265(425.82mV)
Resistance= 675.46
Group 4:
RefDifferential: 422(79.34mV)
Differential: 85(15.98mV)
Resistance= 20.18
Group 5:
RefDifferential: 144(27.07mV)
Differential: 3150(592.20mV)
Resistance= 2191.87
Group 6:
RefDifferential: 90(16.92mV)
Differential: 1995(375.06mV)
Resistance= 2221.10
Group 7:
RefDifferential: 148(27.82mV)
Differential: 3020(567.76mV)
Resistance= 2044.62
Group 8:
RefDifferential: 289(54.33mV)
Differential: 2869(539.37mV)
Resistance= 994.72
Group 9:
RefDifferential: 351(65.99mV)
Differential: 772(145.14mV)
Resistance= 220.38
Group 10:
RefDifferential: 723(135.92mV)
Differential: 710(133.48mV)
Resistance= 98.40
Group 11:
RefDifferential: 130(24.44mV)
Differential: 2780(522.64mV)
Resistance= 2142.74
Group 12:
RefDifferential: 189(35.53mV)
Differential: 621(116.75mV)
Resistance= 329.23
Group 13:
RefDifferential: 193(36.28mV)
Differential: 192(36.10mV)
Resistance= 99.68
Group 14:
RefDifferential: 237(44.56mV)
Differential: 1202(225.98mV)
Resistance= 508.19
Group 15:
RefDifferential: 327(61.48mV)
Differential: 1650(310.20mV)
Resistance= 505.60
Group 16:
RefDifferential: 636(119.57mV)
Differential: 2964(557.23mV)
Resistance= 466.97
Group 17:
RefDifferential: 93(17.48mV)
Differential: 308(57.90mV)
Resistance= 331.85
Group 18:
RefDifferential: 462(86.86mV)
Differential: 3109(584.49mV)
Resistance= 674.29
Group 19:
RefDifferential: 376(70.69mV)
Differential: 3734(701.99mV)
Resistance= 995.07
Group 20:
RefDifferential: 265(49.82mV)
Differential: 2641(496.51mV)
Resistance= 998.60
Group 21:
RefDifferential: 358(67.30mV)
Differential: 3528(663.26mV)
Resistance= 987.45
Group 22:
RefDifferential: 204(38.35mV)
Differential: 305(57.34mV)
Resistance= 149.81
Group 23:
RefDifferential: 90(16.92mV)
Differential: 4187(787.16mV)
Resistance= 4661.53

975 x 1020
Hello!
Getting differential reading from AIN0 (P) and AIN1 (N)
ADC Range: +/- 6.144V (1 bit = 0.188mV)
Hello!
Getting differential reading from AIN0 (P) and AIN1 (N)
ADC Range: +/- 6.144V (1 bit = 0.188mV)
Group 1:
RefDifferential: 119(22.37mV)
Differential: 2426(456.09mV)
Resistance= 2042.73
Group 2:
RefDifferential: 287(53.96mV)
Differential: 948(178.22mV)
Resistance= 330.97
Group 3:
RefDifferential: 348(65.42mV)
Differential: 2356(442.93mV)
Resistance= 678.37
Group 4:
RefDifferential: 480(90.24mV)
Differential: 96(18.05mV)
Resistance= 20.04
Group 5:
RefDifferential: 162(30.46mV)
Differential: 3563(669.84mV)
Resistance= 2203.78
Group 6:
RefDifferential: 103(19.36mV)
Differential: 2271(426.95mV)
Resistance= 2209.26
Group 7:
RefDifferential: 171(32.15mV)
Differential: 3474(653.11mV)
Resistance= 2035.64
Group 8:
RefDifferential: 354(66.55mV)
Differential: 3519(661.57mV)
Resistance= 996.06
Group 9:
RefDifferential: 432(81.22mV)
Differential: 932(175.22mV)
Resistance= 216.17
Group 10:
RefDifferential: 874(164.31mV)
Differential: 878(165.06mV)
Resistance= 100.66
Group 11:
RefDifferential: 160(30.08mV)
Differential: 3194(600.47mV)
Resistance= 2000.24
Group 12:
RefDifferential: 221(41.55mV)
Differential: 731(137.43mV)
Resistance= 331.43
Group 13:
RefDifferential: 223(41.92mV)
Differential: 222(41.74mV)
Resistance= 99.75
Group 14:
RefDifferential: 272(51.14mV)
Differential: 1372(257.94mV)
Resistance= 505.42
Group 15:
RefDifferential: 375(70.50mV)
Differential: 1905(358.14mV)
Resistance= 509.02
Group 16:
RefDifferential: 722(135.74mV)
Differential: 3371(633.75mV)
Resistance= 467.83
Group 17:
RefDifferential: 107(20.12mV)
Differential: 350(65.80mV)
Resistance= 327.76
Group 18:
RefDifferential: 532(100.02mV)
Differential: 3564(670.03mV)
Resistance= 671.26
Group 19:
RefDifferential: 433(81.40mV)
Differential: 4294(807.27mV)
Resistance= 993.67
Group 20:
RefDifferential: 301(56.59mV)
Differential: 3008(565.50mV)
Resistance= 1001.33
Group 21:
RefDifferential: 409(76.89mV)
Differential: 4046(760.65mV)
Resistance= 991.22
Group 22:
RefDifferential: 232(43.62mV)
Differential: 348(65.42mV)
Resistance= 150.30
Group 23:
RefDifferential: 102(19.18mV)
Differential: 4749(892.81mV)
Resistance= 4665.19
  
```

Figure 92 Two groups complete test results displayed in Arduino IDE

Test code:

```
#include <Wire.h>
#include <Adafruit_ADS1X15.h>
int frequency = 1450; //Set frequency in Hertz
double delayTime = 1000000 / (frequency * 2);
double delayseconds = 1000/(frequency * 2);
Adafruit_ADS1115 ads1115;
double a1 = 0, f=1;
float refR = 100.2;

void setup(void)
{
  pinMode(3, OUTPUT);
  pinMode(2, OUTPUT);
  pinMode(5, OUTPUT);
  pinMode(6, OUTPUT);
  pinMode(7, OUTPUT);
  pinMode(8, OUTPUT);
  pinMode(9, OUTPUT);
  pinMode(10, OUTPUT);
  pinMode(11, OUTPUT);
  pinMode(12, OUTPUT);
  pinMode(13, OUTPUT);
  pinMode(14, OUTPUT);
  pinMode(15, OUTPUT);
  pinMode(16, OUTPUT);
  pinMode(17, OUTPUT);
  pinMode(18, OUTPUT);
  pinMode(19, OUTPUT);
  pinMode(22, OUTPUT);
  pinMode(23, OUTPUT);
  pinMode(24, OUTPUT);
  pinMode(25, OUTPUT);
  pinMode(26, OUTPUT);
  pinMode(27, OUTPUT);
  pinMode(28, OUTPUT);
  pinMode(29, OUTPUT);

  Serial.begin(115200);
  Serial.println("Hello!");

  Serial.println("Getting differential reading from AIN0 (P) and AIN1 (N)");
  Serial.println("ADC Range: +/- 6.144V (1 bit = 0.188mV) ");

  ads1115.begin();
}

void loop(void)
{
  int16_t results1;
  int16_t results2;
  double T = 0;
  double resistance = 0,a=0,b=0;
  digitalWrite(3, HIGH);
  digitalWrite(5, HIGH);
  digitalWrite(6, HIGH);
  digitalWrite(7, HIGH);
  digitalWrite(8, HIGH);
  digitalWrite(9, HIGH);
```

```
digitalWrite(10, HIGH);  
digitalWrite(11, HIGH);  
digitalWrite(12, HIGH);  
digitalWrite(13, HIGH);  
digitalWrite(14, HIGH);  
digitalWrite(15, HIGH);  
digitalWrite(16, HIGH);  
digitalWrite(17, HIGH);  
digitalWrite(18, HIGH);  
digitalWrite(19, HIGH);  
digitalWrite(22, HIGH);  
digitalWrite(23, HIGH);  
digitalWrite(24, HIGH);  
digitalWrite(25, HIGH);  
digitalWrite(26, HIGH);  
digitalWrite(27, HIGH);  
digitalWrite(28, HIGH);  
digitalWrite(29, HIGH);
```

```
T = delayTime;  
digitalWrite(2, LOW);  
delayMicroseconds(T+430);
```

```
digitalWrite(2, HIGH);  
delayMicroseconds(T);  
a1=a1+1;
```

```
if (a1>=1600*f and f==1)  
{  
  digitalWrite(5, LOW);  
  f=2;  
  results1 = abs(ads1115.readADC_Differential_0_1());  
  delay(100);  
  b=abs(results1);  
  Serial.println("Group 1: ");  
  Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);  
  Serial.println("mV");  
  results2 = ads1115.readADC_Differential_2_3();  
  a=abs(results2);  
  Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");  
  resistance = (a/b) * refR;  
  Serial.print("Resistance= "); Serial.println(resistance);  
  digitalWrite(5, HIGH);  
}  
if (a1>=1600*f and f==2)  
{  
  digitalWrite(6, LOW);  
  f=3;  
  results1 = ads1115.readADC_Differential_0_1();  
  delay(100);  
  b=abs(results1);  
  Serial.println("Group 2: ");  
  Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);  
  Serial.println("mV");  
  results2 = ads1115.readADC_Differential_2_3();  
  a=abs(results2);  
  Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");  
  resistance = (a/b) * refR;  
  Serial.print("Resistance= "); Serial.println(resistance);  
  digitalWrite(6, HIGH);
```

```
}
if (a1>=1600*f and f==3)
{
  digitalWrite(7, LOW);
  f=4;
  results1 = ads1115.readADC_Differential_0_1();
  delay(100);
  b=abs(results1);
  Serial.println("Group 3: ");
  Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
  Serial.println("mV");
  results2 = ads1115.readADC_Differential_2_3();
  a=abs(results2);
  Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
  resistance = (a/b) * refR;
  Serial.print("Resistance= "); Serial.println(resistance);
  digitalWrite(7, HIGH);
}
if (a1>=1600*f and f==4)
{
  digitalWrite(8, LOW);
  f=5;
  results1 = ads1115.readADC_Differential_0_1();
  delay(100);
  b=abs(results1);
  Serial.println("Group 4: ");
  Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
  Serial.println("mV");
  results2 = ads1115.readADC_Differential_2_3();
  a=abs(results2);
  Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
  resistance = (a/b) * refR;
  Serial.print("Resistance= "); Serial.println(resistance);
  digitalWrite(8, HIGH);
}
if (a1>=1600*f and f==5)
{
  digitalWrite(9, LOW);
  f=6;
  results1 = ads1115.readADC_Differential_0_1();
  delay(100);
  b=abs(results1);
  Serial.println("Group 5: ");
  Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
  Serial.println("mV");
  results2 = ads1115.readADC_Differential_2_3();
  a=abs(results2);
  Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
  resistance = (a/b) * refR;
  Serial.print("Resistance= "); Serial.println(resistance);
  digitalWrite(9, HIGH);
}
if (a1>=1600*f and f==6)
{
  digitalWrite(10, LOW);
  f=7;
  results1 = ads1115.readADC_Differential_0_1();
  delay(100);
  b=abs(results1);
  Serial.println("Group 6: ");
```

```
Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
Serial.println("mV");
results2 = ads1115.readADC_Differential_2_3();
a=abs(results2);
Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
resistance = (a/b) * refR;
Serial.print("Resistance= "); Serial.println(resistance);
digitalWrite(10, HIGH);
}
if (a1>=1600*f and f==7)
{
digitalWrite(11, LOW);
f=8;
results1 = ads1115.readADC_Differential_0_1();
delay(100);
b=abs(results1);
Serial.println("Group 7: ");
Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
Serial.println("mV");
results2 = ads1115.readADC_Differential_2_3();
a=abs(results2);
Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
resistance = (a/b) * refR;
Serial.print("Resistance= "); Serial.println(resistance);
digitalWrite(11, HIGH);
}
if (a1>=1600*f and f==8)
{
digitalWrite(12, LOW);
f=9;
results1 = ads1115.readADC_Differential_0_1();
delay(100);
b=abs(results1);
Serial.println("Group 8: ");
Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
Serial.println("mV");
results2 = ads1115.readADC_Differential_2_3();
a=abs(results2);
Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
resistance = (a/b) * refR;
Serial.print("Resistance= "); Serial.println(resistance);
digitalWrite(12, HIGH);
}
if (a1>=1600*f and f==9)
{
digitalWrite(13, LOW);
f=10;
results1 = ads1115.readADC_Differential_0_1();
delay(100);
b=abs(results1);
Serial.println("Group 9: ");
Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
Serial.println("mV");
results2 = ads1115.readADC_Differential_2_3();
a=abs(results2);
Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
resistance = (a/b) * refR;
Serial.print("Resistance= "); Serial.println(resistance);
digitalWrite(13, HIGH);
}
```



```
    if (a1>=1600*f and f==10)
    {
        digitalWrite(14, LOW);
        f=11;

        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 10: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
        Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
        resistance = (a/b) * refR;
        Serial.print("Resistance= "); Serial.println(resistance);
        digitalWrite(14, HIGH);
    }

    if (a1>=1600*f and f==11)
    {
        digitalWrite(15, LOW);
        f=12;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 11: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
        Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
        resistance = (a/b) * refR;
        Serial.print("Resistance= "); Serial.println(resistance);
        digitalWrite(15, HIGH);
    }

    if (a1>=1600*f and f==12)
    {
        digitalWrite(16, LOW);
        f=13;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 12: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
        Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
        resistance = (a/b) * refR;
        Serial.print("Resistance= "); Serial.println(resistance);
        digitalWrite(16, HIGH);
    }

    if (a1>=1600*f and f==13)
    {
        digitalWrite(17, LOW);
        f=14;
        results1 = ads1115.readADC_Differential_0_1();
```

```
delay(100);
b=abs(results1);
Serial.println("Group 13: ");
Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
Serial.println("mV");
results2 = ads1115.readADC_Differential_2_3();
a=abs(results2);
Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
resistance = (a/b) * refR;
Serial.print("Resistance= "); Serial.println(resistance);
digitalWrite(17, HIGH);
}

    if (a1>=1600*f and f==14)
    {
        digitalWrite(18, LOW);
        f=15;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 14: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
        Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
        resistance = (a/b) * refR;
        Serial.print("Resistance= "); Serial.println(resistance);
        digitalWrite(18, HIGH);
    }

    if (a1>=1600*f and f==15)
    {
        digitalWrite(19, LOW);
        f=16;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 15: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
        Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
        resistance = (a/b) * refR;
        Serial.print("Resistance= "); Serial.println(resistance);
        digitalWrite(19, HIGH);
    }

    if (a1>=1600*f and f==16)
    {
        digitalWrite(22, LOW);
        f=17;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 16: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
```

```
Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
resistance = (a/b) * refR;
Serial.print("Resistance= "); Serial.println(resistance);
digitalWrite(22, HIGH);
}

    if (a1>=1600*f and f==17)
    {
        digitalWrite(23, LOW);
        f=18;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 17: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
        Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
        resistance = (a/b) * refR;
        Serial.print("Resistance= "); Serial.println(resistance);
        digitalWrite(23, HIGH);
    }

    if (a1>=1600*f and f==18)
    {
        digitalWrite(24, LOW);
        f=19;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 18: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
        Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
        resistance = (a/b) * refR;
        Serial.print("Resistance= "); Serial.println(resistance);
        digitalWrite(24, HIGH);
    }

    if (a1>=1600*f and f==19)
    {
        digitalWrite(25, LOW);
        f=20;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 19: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
        Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
        resistance = (a/b) * refR;
        Serial.print("Resistance= "); Serial.println(resistance);
        digitalWrite(25, HIGH);
    }
```

```
    if (a1>=1600*f and f==20)
    {
        digitalWrite(26, LOW);
        f=21;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 20: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
        Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
        resistance = (a/b) * refR;
        Serial.print("Resistance= "); Serial.println(resistance);
        digitalWrite(26, HIGH);
    }

    if (a1>=1600*f and f==21)
    {
        digitalWrite(27, LOW);
        f=22;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 21: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
        Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
        resistance = (a/b) * refR;
        Serial.print("Resistance= "); Serial.println(resistance);
        digitalWrite(27, HIGH);
    }

    if (a1>=1600*f and f==22)
    {
        digitalWrite(28, LOW);
        f=23;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
        Serial.println("Group 22: ");
        Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
        Serial.println("mV");
        results2 = ads1115.readADC_Differential_2_3();
        a=abs(results2);
        Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
        resistance = (a/b) * refR;
        Serial.print("Resistance= "); Serial.println(resistance);
        digitalWrite(28, HIGH);
    }

    if (a1>=1600*f and f==23)
    {
        digitalWrite(29, LOW);
        f=1;
        a1=0;
        results1 = ads1115.readADC_Differential_0_1();
        delay(100);
        b=abs(results1);
```

```
Serial.println("Group 23: ");
Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
Serial.println("mV");
results2 = ads1115.readADC_Differential_2_3();
a=abs(results2);
Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188); Serial.println("mV");
resistance = (a/b) * refR;
Serial.print("Resistance= "); Serial.println(resistance);
digitalWrite(29, HIGH);
}
}
```

Conclusion:

After testing, it can be concluded that the system into a PCB work successfully with the supply of Arduino Mega board, and at the same time, the system has the capability to measure resistance and automatically switch within the terminals connected.

Automated electrode-switch salt watcher system (demo) test plan:

Aim:

The aim of the automated electrode-switch salt watcher system demo test is to test whether this demon system is able to stably detect the value of the voltage and current to be measured and switch the electrode set automatically successfully. Finally, if required, test if the values can be displayed on external screen.

Hypothesis:

When the whole system inputs whatever DC signal source or AC square wave signal source to measure the same resistor, the measurement results keep stable relatively. Also, the resistors to be measured could be switched automatically. If meet both requirements mentioned above, the system is judged to pass the test.

Variables:

Table 22 Variables in Automated electrode-switch salt watcher system demo test

Nr.	Property	Vary/Measure	Value	Unit
1	Power for whole system	Vary	5.0	V
2	Resistance	Measure	270, 510, 2000	Ω
3	Differential voltage of reference resistor (in DC)	Vary	27-100	mV
4	Differential voltage of resistor tested (in DC)	Vary	600-1500	mV
5	Differential voltage of reference resistor (in AC)	Vary	70-240	mV
6	Differential voltage of resistor tested (in AC)	Vary	250-580	mV
7	Frequency (in AC)	Vary	800	Hz
8	Output digital signal from Arduino board	Vary	\	\

Testing Tools:

Table 23 Testing tools in Automated electrode-switch salt watcher system demo test

Nr.	Item	Demands
1	Laptop	\
3	Connecting cable (USB Micro B)	\
4	Oscilloscope (DSO5202P)	\
5	Mobile phone	Photography and video
6	Jumper cables	\
7	Breadboard	\
8	Multimeter	\
9	Arduino Uno board	\
10	Automated electrode-switch salt watcher system	\

Method (For DC test):

1. Layout all components reasonably on breadboard.
2. Connect Arduino Uno 5V power to breadboard as power source of the whole system (including the voltage & current measuring sub-system).
3. Connect Arduino Uno board with laptop, enabling Arduino board as power supply.
4. Upload code into Arduino Uno board and open IDE serial monitor.
5. Observe and record the results displayed. For each resistor set, take down 20 groups of data.
6. Disconnect all wires and organize devices and instruments and components.

Method (For AC test):

1. Layout all components reasonably on breadboard.
2. Connect Arduino Uno 5V power to breadboard as power source of the system excluding the voltage & current measuring sub-system.
3. Connect signal generation sub-system with voltage & current measuring sub-system, using AC square waves as power source of that sub-system.
4. Connect Arduino Uno board with laptop, enabling Arduino board as power supply.
5. Upload code into Arduino Uno board and open IDE serial monitor.
6. Observe and record the results displayed. For each resistor set, take down 20 groups of data.
7. Disconnect all wires and organize devices and instruments and components.
8. Compare the data measured in AC test and the data collected in DC test.

Expected results:

In both DC and AC test, the differential voltage of reference resistor and measured resistor and corresponding calculated resistance would be displayed in Arduino IDE serial monitor. After comparison, it will be found the value tested in two tests are almost equal correspondingly despite of some slight differences.

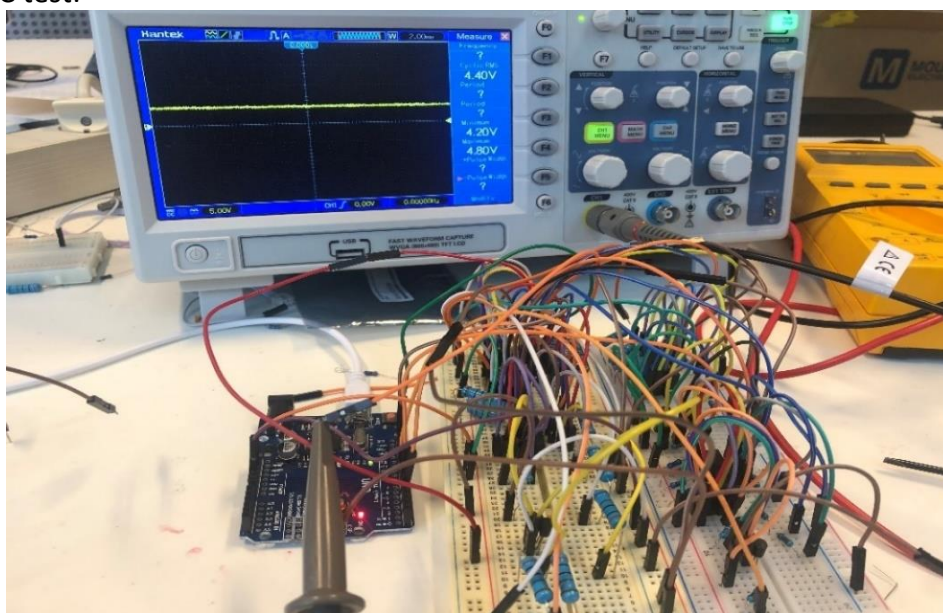
Test results**① DC test:**

Figure 93 DC test of Automated electrode-switch salt watcher system diagram

Table 24 DC test for group1

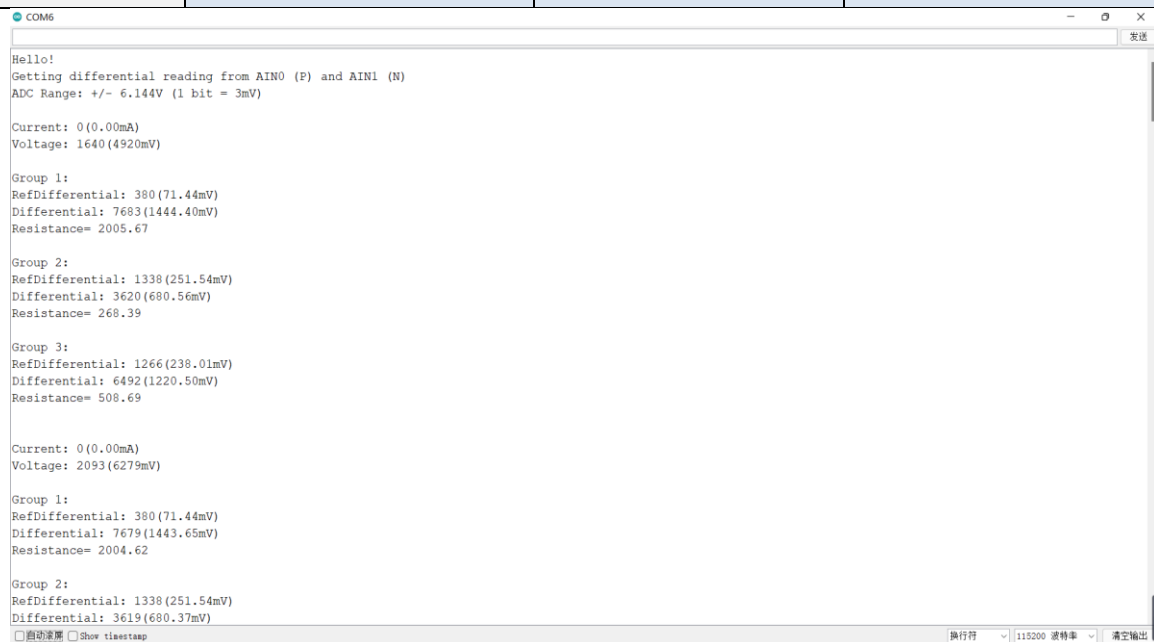
Nr.	Voltage of reference resistor (mV)	Voltage of resistor to measured (mV)	Resistance calculated (Ω)
1	71.44	1444.4	2005.66
2	71.44	1443.65	2004.62
3	71.45	1444.6	2005.66
4	71.44	1443.55	2004.48
5	71.44	1443.76	2004.78
6	71.44	1443.75	2004.76
7	71.44	1444.23	2005.43
8	71.44	1446.01	2007.90
9	71.44	1444.45	2005.73
10	71.44	1443.65	2004.62
11	71.44	1446.15	2008.09
12	71.44	1443.99	2005.09
13	71.46	1443.95	2004.48
14	71.45	1444.85	2006.01
15	71.44	1443.65	2004.62
16	71.44	1443.78	2004.80
17	71.44	1444.65	2006.01
18	71.44	1444.55	2005.87
19	71.44	1443.69	2004.68
20	71.43	1444.91	2006.65

Table 25 DC test for group2

Nr.	Voltage of reference resistor (mV)	Voltage of resistor to measured (mV)	Resistance calculated (Ω)
1	251.54	680.56	268.39
2	251.54	680.37	268.32
3	251.54	680.98	268.56
4	251.54	680.58	268.40
5	251.54	681.06	268.59
6	251.53	680.76	268.48
7	251.54	680.64	268.42
8	251.52	680.78	268.50
9	251.51	680.76	268.50
10	251.54	680.95	268.55
11	251.54	682.01	268.97
12	251.54	679.86	268.12
13	251.54	680.56	268.39
14	251.54	681.16	268.63
15	251.54	680.24	268.27
16	251.54	680.88	268.52
17	251.53	680.16	268.25
18	251.54	680.57	268.40
19	251.55	682.76	269.25
20	251.54	680.47	268.36

Table 26 DC test for group3

Nr.	Voltage of reference resistor (mV)	Voltage of resistor to measured (mV)	Resistance calculated (Ω)
1	238.01	1220.5	508.69
2	238.01	1220.95	508.88
3	238.03	1220.56	508.67
4	238.01	1220.98	508.89
5	238.01	1220.9	508.86
6	238.01	1220.68	508.77
7	238.02	1221.45	509.07
8	238.03	1220.51	508.65
9	238.01	1220.5	508.69
10	238.01	1220.66	508.76
11	238.01	1220.81	508.82
12	238.01	1219.57	508.30
13	237.99	1218.57	507.93
14	238.01	1220.58	508.73
15	238.02	1223.01	509.72
16	238.01	1220.58	508.73
17	238.01	1221.55	509.13
18	238.01	1220.51	508.70
19	238.01	1222.08	509.35
20	238.04	1220.16	508.49



```

COM6
Hello!
Getting differential reading from AIN0 (P) and AIN1 (N)
ADC Range: +/- 6.144V (1 bit = 3mV)

Current: 0(0.00mA)
Voltage: 1640(4920mV)

Group 1:
RefDifferential: 380(71.44mV)
Differential: 7683(1444.40mV)
Resistance= 2005.67

Group 2:
RefDifferential: 1338(251.54mV)
Differential: 3620(680.56mV)
Resistance= 268.39

Group 3:
RefDifferential: 1266(238.01mV)
Differential: 6492(1220.50mV)
Resistance= 508.69

Current: 0(0.00mA)
Voltage: 2093(6279mV)

Group 1:
RefDifferential: 380(71.44mV)
Differential: 7679(1443.65mV)
Resistance= 2004.62

Group 2:
RefDifferential: 1338(251.54mV)
Differential: 3619(680.37mV)
  
```

Figure 94 Partial test results displayed in Arduino IDE serial monitor

Test code:

```
#include <Wire.h>
#include <Adafruit_ADS1X15.h>

Adafruit_ADS1115 ads1115;

void setup() {

  Serial.begin(115200);
  Serial.println("Hello!");

  Serial.println("Getting differential reading from AIN0 (P) and AIN1 (N)");
  Serial.println("ADC Range: +/- 6.144V (1 bit = 3mV)");
  ads1115.begin();
  pinMode(5, OUTPUT);
  pinMode(6, OUTPUT);
  pinMode(7, OUTPUT);
}

void loop() {

  int16_t results1;
  int16_t results2;
  double I_results1;
  double b=0,a=0,resistance=0;
  digitalWrite(5, HIGH);
  digitalWrite(6, HIGH);
  digitalWrite(7, HIGH);
  delay(100);
  results1 = ads1115.readADC_Differential_0_1();
  I_results1 = results1 * 3/99.2;
  results2 = ads1115.readADC_Differential_2_3();
  Serial.print("\n");
  Serial.print("Current: "); Serial.print(results1); Serial.print("("); Serial.print(I_results1);
  Serial.println("mA");
  Serial.print("Voltage: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 3);
  Serial.println("mV)\n");
  delay(2000);

  digitalWrite(5, LOW);
  delay(100);
  results1 = ads1115.readADC_Differential_0_1();
  b=abs(results1);
  Serial.println("Group 1: ");
  Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
  Serial.println("mV)");
  results2 = ads1115.readADC_Differential_2_3();
  a=abs(results2);
  Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188);
  Serial.println("mV)");
  resistance = (a/b) * 99.2;
```

```
Serial.print("Resistance= "); Serial.println(resistance); Serial.print("\n");
delay(2000);
digitalWrite(5, HIGH);

digitalWrite(6, LOW);
results1 = ads1115.readADC_Differential_0_1();
b=abs(results1);
Serial.println("Group 2: ");
Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
Serial.println("mV");
results2 = ads1115.readADC_Differential_2_3();
a=abs(results2);
Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188);
Serial.println("mV");
resistance = (a/b) * 99.2;
Serial.print("Resistance= "); Serial.println(resistance); Serial.print("\n");
delay(2000);
digitalWrite(6, HIGH);

digitalWrite(7, LOW);
results1 = ads1115.readADC_Differential_0_1();
b=abs(results1);
Serial.println("Group 3: ");
Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
Serial.println("mV");
results2 = ads1115.readADC_Differential_2_3();
a=abs(results2);
Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188);
Serial.println("mV");
resistance = (a/b) * 99.2;
Serial.print("Resistance= "); Serial.println(resistance); Serial.print("\n");
delay(2000);
digitalWrite(7, HIGH);
}
```


② AC test:

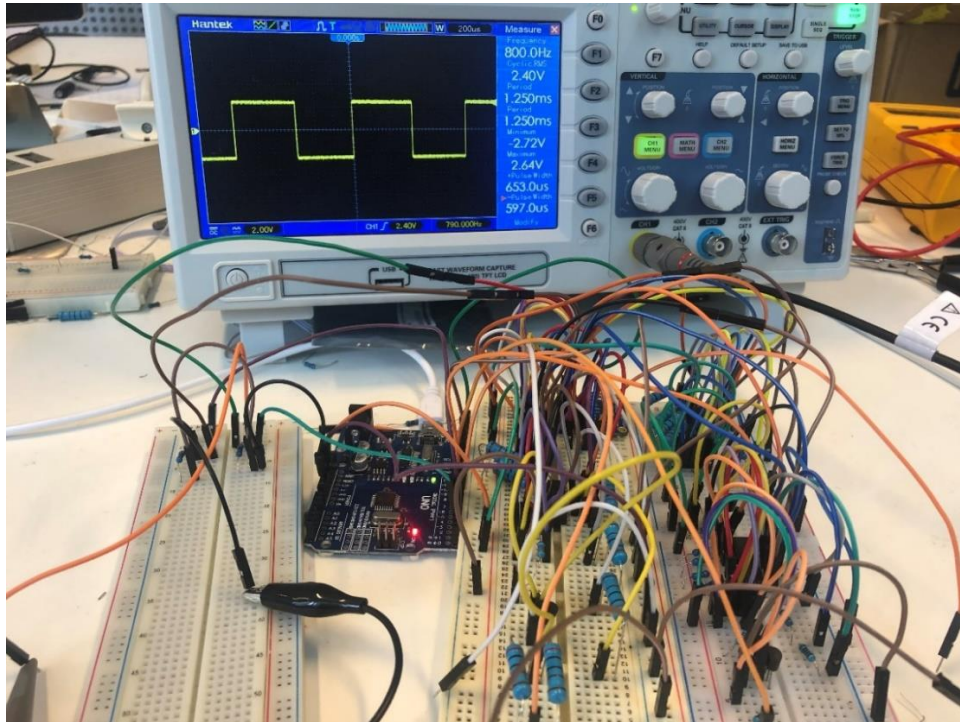


Figure 95 DC test of Automated electrode-switch salt watcher system diagram

Table 27 AC test for 2000Ω resistor

Nr.	Voltage of reference resistor (mV)	Voltage of resistor to measured (mV)	Resistance calculated (Ω)
1	28.2	565.69	2006.00
2	27.89	563.12	2019.09
3	28.12	565.62	2011.46
4	28.18	567.69	2014.52
5	28.11	568.78	2023.42
6	28.19	568.19	2015.58
7	27.9	566.01	2028.72
8	28.21	566.99	2009.90
9	28.2	567.79	2013.45
10	28.25	568.69	2013.07
11	28.2	567.12	2011.07
12	28.36	571.69	2015.84
13	28.2	570.69	2023.73
14	28.34	568.69	2006.68
15	28.31	569.13	2010.36
16	28.12	566.65	2015.12
17	28.1	565.69	2013.14
18	28.21	569.67	2019.40
19	28.04	565.77	2017.73
20	28.07	565.53	2014.72

Table 28 AC test for 270Ω resistor

Nr.	Voltage of reference resistor (mV)	Voltage of resistor to measured (mV)	Resistance calculated (Ω)
1	97.38	262.45	269.51
2	97.95	264.89	270.44
3	97.65	263.59	269.93
4	97.91	264.62	270.27
5	97.12	264.19	272.03
6	97.29	262.98	270.31
7	97.69	262.75	268.96
8	97.8	262.49	268.40
9	98.02	263.12	268.44
10	97.87	263.58	269.32
11	97.65	263.59	269.93
12	97.86	263.11	268.87
13	97.46	263.42	270.29
14	97.85	262.89	268.67
15	97.12	263.46	271.27
16	97.88	262.99	268.69
17	97.96	262.96	268.44
18	97.95	267.09	272.68
19	97.9	263.59	269.25
20	97.38	262.78	269.85

Table 29 AC test for 510Ω resistor

Nr.	Voltage of reference resistor (mV)	Voltage of resistor to measured (mV)	Resistance calculated (Ω)
1	72.19	372.24	515.64
2	73.7	379.76	515.28
3	72.86	375.24	515.02
4	72.42	374.32	516.88
5	72.76	374.98	515.37
6	72.54	373.97	515.54
7	73.46	378.56	515.33
8	72.77	377.62	518.93
9	72.2	373.87	517.83
10	72.16	374.2	518.57
11	72.19	373.24	517.03
12	72.78	374.04	513.93
13	72.06	371.94	516.16
14	72.89	378.64	519.47
15	73.08	373.63	511.26
16	73.96	379.14	512.63
17	74.06	380.93	514.36
18	73.79	379.27	513.99
19	72.56	374.26	515.80
20	72.65	376.64	518.43

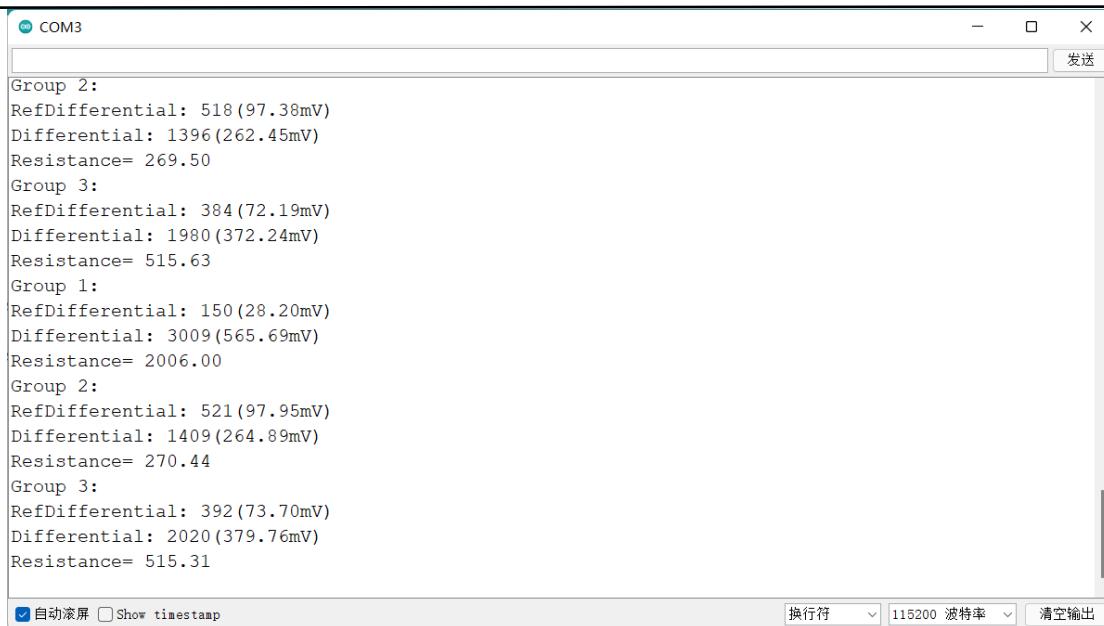


Figure 96 Partial test results of AC test

Test code:

```
#include <Wire.h>

#include <Adafruit_ADS1X15.h>

int frequency = 848; //Set frequency in Hertz

double delayTime = 1000000 / (frequency * 2);

double delayseconds = 1000/(frequency * 2);

Adafruit_ADS1115 ads1115;

double n = 0,x=0,p=0,f=1;

float refR = 100;

void setup(void)
{
  pinMode(3, OUTPUT);
  pinMode(2, OUTPUT);
  pinMode(5, OUTPUT);
  pinMode(6, OUTPUT);
  pinMode(7, OUTPUT);
  Serial.begin(115200);
  Serial.println("Hello!");
```

```
Serial.println("Getting differential reading from AIN0 (P) and AIN1 (N)");  
Serial.println("ADC Range: +/- 6.144V (1 bit = 0.188mV) ");  
ads1115.begin();  
}
```

```
void loop(void)  
{  
    int16_t results1;  
    int16_t results2;  
    double T = 0;  
    double resistance = 0,a=0,b=0;  
    digitalWrite(3, HIGH);  
    digitalWrite(5, HIGH);  
    digitalWrite(6, HIGH);  
    digitalWrite(7, HIGH);  
    if (frequency>=100)  
    {  
        T = delayTime;  
        digitalWrite(2, LOW);  
        delayMicroseconds(T);  
        digitalWrite(2, HIGH);  
        delayMicroseconds(T);  
    }  
    else  
    {  
        T = delayseconds;  
        digitalWrite(2, LOW);  
        delay(T);  
        digitalWrite(2, HIGH);  
        delay(T);  
    }
```

```
}  
  
n=n+1;  
  
x=x+1;  
  
p=p+1;  
  
if (n>=1600 and f==1)  
{  
    digitalWrite(5, LOW);  
  
    f=2;  
  
    results1 = ads1115.readADC_Differential_0_1();  
  
    b=abs(results1);  
  
    Serial.println("Group 1: ");  
  
    Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);  
    Serial.println("mV");  
  
    results2 = ads1115.readADC_Differential_2_3();  
  
    a=abs(results2);  
  
    Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188);  
    Serial.println("mV");  
  
    resistance = (a/b) * refR;  
  
    Serial.print("Resistance= "); Serial.println(resistance);  
  
    digitalWrite(5, HIGH);  
}  
  
if (x>=3200 and f==2)  
{  
    digitalWrite(6, LOW);  
  
    f=3;  
  
    results1 = ads1115.readADC_Differential_0_1();  
  
    b=abs(results1);  
  
    Serial.println("Group 2: ");  
  
    Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);  
    Serial.println("mV");  
  
    results2 = ads1115.readADC_Differential_2_3();  
  
    a=abs(results2);
```

```
Serial.print("Differential: "); Serial.print(results2); Serial.print(""); Serial.print(results2 * 0.188);
Serial.println("mV");

resistance = (a/b) * refR;

Serial.print("Resistance= "); Serial.println(resistance);

digitalWrite(6, HIGH);

}

if (p>=4800 and f==3)

{

digitalWrite(7, LOW);

f=1;

n=0;

x=0;

p=0;

results1 = ads1115.readADC_Differential_0_1();

b=abs(results1);

Serial.println("Group 3: ");

Serial.print("RefDifferential: "); Serial.print(results1); Serial.print(""); Serial.print(results1 * 0.188);
Serial.println("mV");

results2 = ads1115.readADC_Differential_2_3();

a=abs(results2);

Serial.print("Differential: "); Serial.print(results2); Serial.print(""); Serial.print(results2 * 0.188);
Serial.println("mV");

resistance = (a/b) * refR;

Serial.print("Resistance= "); Serial.println(resistance);

digitalWrite(7, HIGH);

}

}
```

Conclusion:

After testing, conclusion can be derived that when the whole system inputs both DC signal source or AC square wave signal source to measure the same resistor, the resistance values of the resistors can be both measured and the results keep relatively stable despite some fluctuation. Also, figures shown above can prove the resistors to be measured could be switched automatically in certain frequency (AC) or certain time interval (DC). Two requirements have been met, so the system is judged to pass the test.

Automatic electrode-switch sub-system test plan:

Aim:

The aim of the automated electrode-switch salt watcher system test is to test whether this system is able to stably detect the value of the voltage and current to be measured, and switch the electrode set automatically successfully. Finally, if required, test if the values can be displayed on external screen.

Hypothesis:

When the whole system inputs DC 5V source to measure 3 group resistance values, the measurement results (differential voltage and current) change and displayed in Arduino IDE serial monitor circularly.

Variables:

Table 30 Variables in Automatic electrode-switch sub-system test

Nr.	Property	Vary/Measure	Value	Unit
1	Power for whole system	Vary	5.0	V
2	Resistance	Measure	270, 510, 2000	Ω
3	Differential voltage	Measure	780-1550	mV
4	Current	Measure	0.7-3	mA
5	Output digital signal from Arduino board	Vary	\	\

Testing tools:

Table 31 Testing tools in Automatic electrode-switch sub-system test

Nr.	Item	Remark
1	Laptop	\
2	Connecting cable (USB Micro B)	\
3	Mobile phone	Photography and video
4	Jumper cables	\
5	Breadboard	\
6	Resistor	100 Ω , 270, 1k Ω , 2k Ω , 10k Ω
7	Transistor	\
8	ADS1115	AD converter
9	TLP521-4	Optocoupler
10	Arduino Uno board	\

Method:

1. Layout all components reasonably on breadboard.
2. Connect Arduino Uno 5V power to breadboard as power source of the switch sub-system.
3. Connect Arduino Uno board with laptop, enabling Arduino board as power supply.
4. Upload code into Arduino Uno board and open IDE serial monitor.
5. Observe and record the results displayed.
6. Disconnect all wires and organize devices and instruments and components.

Test results

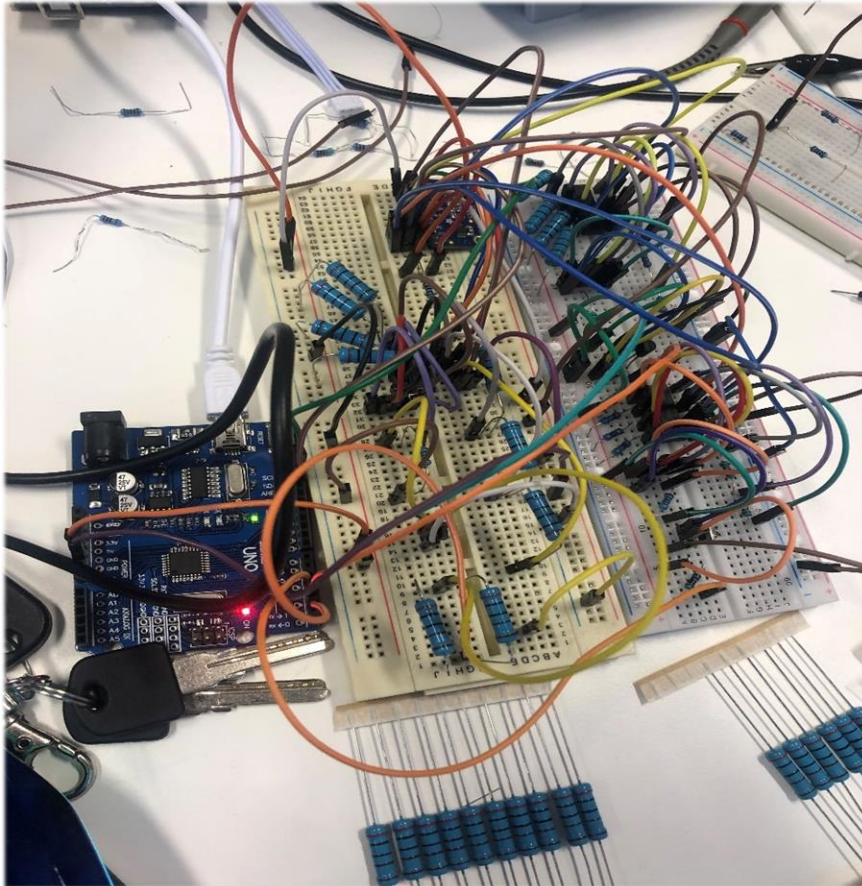


Figure 97 Switch sub-system test diagram

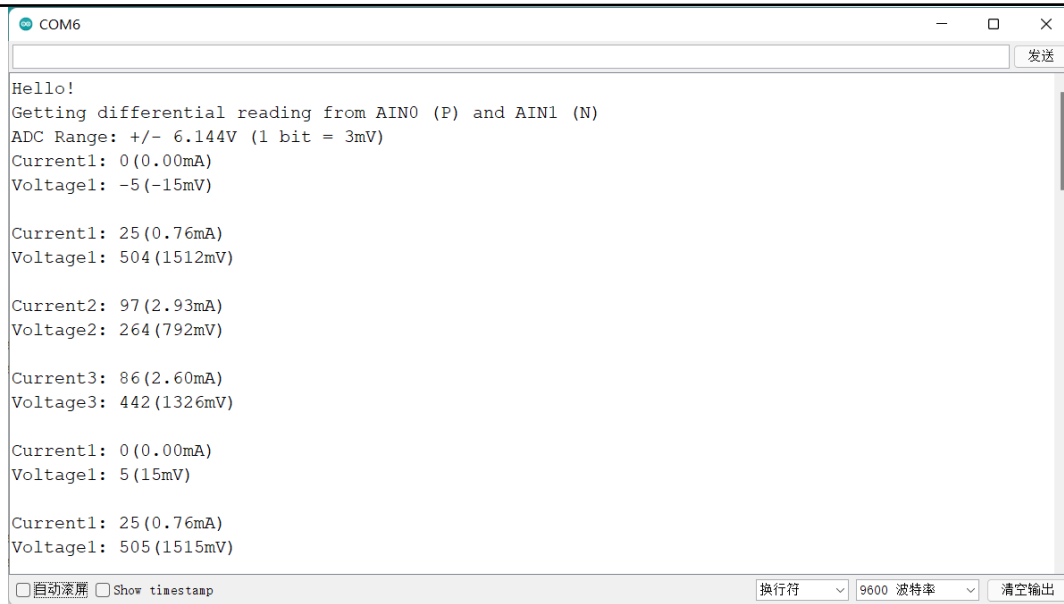


Figure 98 Test 1 results in IDE serial monitor

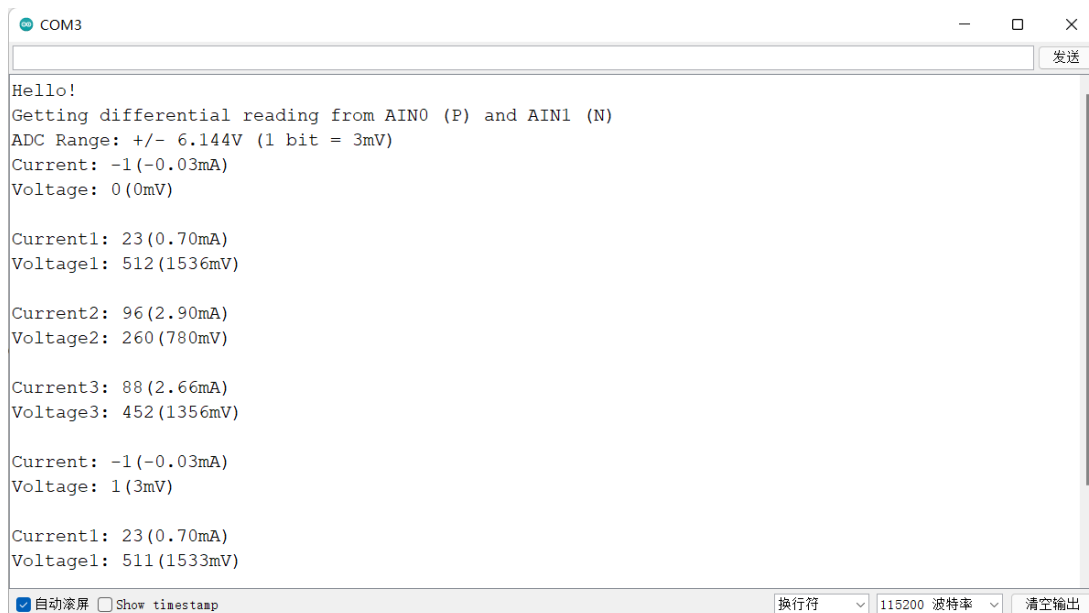


Figure 99 Test 2 results in IDE serial monitor

Test code:

```
#include <Wire.h>

#include <Adafruit_ADS1X15.h>

Adafruit_ADS1015 ads1115;

void setup() {

  Serial.begin(9600);
```

```
Serial.println("Hello!");
```

```
Serial.println("Getting differential reading from AIN0 (P) and AIN1 (N)");
```

```
Serial.println("ADC Range: +/- 6.144V (1 bit = 3mV)");
```

```
ads1115.begin();
```

```
pinMode(2, OUTPUT);
```

```
pinMode(3, OUTPUT);
```

```
}
```

```
void loop() {
```

```
int16_t results1;
```

```
int16_t results2;
```

```
double I_results1;
```

```
digitalWrite(2, HIGH);
```

```
digitalWrite(3, HIGH);
```

```
results1 = ads1115.readADC_Differential_0_1();
```

```
I_results1 = results1 * 3/99.2;
```

```
results2 = ads1115.readADC_Differential_2_3();
```

```
Serial.print("Current1: "); Serial.print(results1); Serial.print(" "); Serial.print(I_results1);  
Serial.println("mA");
```

```
Serial.print("Voltage1: "); Serial.print(results2); Serial.print(" "); Serial.print(results2 * 3);  
Serial.println("mV");
```

```
delay(2000);
```

```
digitalWrite(2, LOW);
```

```
results1 = ads1115.readADC_Differential_0_1();
```

```
I_results1 = results1 * 3/99.2;
```

```
results2 = ads1115.readADC_Differential_2_3();
```

```
Serial.print("Current1: "); Serial.print(results1); Serial.print(" "); Serial.print(I_results1);  
Serial.println("mA");
```

```
Serial.print("Voltage1: "); Serial.print(results2); Serial.print(""); Serial.print(results2 * 3);  
Serial.println("mV");  
  
digitalWrite(2,HIGH);  
  
delay(3000);  
  
  
digitalWrite(3, LOW);  
  
results1 = ads1115.readADC_Differential_0_1();  
  
I_results1 = results1 * 3/99.2;  
  
results2 = ads1115.readADC_Differential_2_3();  
  
Serial.print("Current2: "); Serial.print(results1); Serial.print(""); Serial.print(I_results1);  
Serial.println("mA");  
  
Serial.print("Voltage2: "); Serial.print(results2); Serial.print(""); Serial.print(results2 * 3);  
Serial.println("mV");  
  
delay(3000);  
  
  
}
```

Conclusion:

It can be concluded from the test results that by coding it is feasible to switch the optocoupler in certain time interval and there is corresponding voltage detected by ADS1115, as shown in the Arduino IDE serial monitor. Therefore, it proved the function and feasibility of this switch sub-system.

Signal generation sub-system test plan:

Aim:

The aim of signal generation sub-system test is mainly threefold. The first aim is to test whether the properties of the equivalent AC square wave signal sources generated by Arduino board with some voltage divider resistors can meet requirements. Furtherly, test stability of the frequency and amplitude of the square waves. Finally, the display on the oscilloscope validates the subsystem's practicality.

Hypothesis:

Theoretically, using Arduino board as power source and some voltage divider resistors, could equally generate the AC square waves as source of external circuit. Besides, the amplitude of square waves can be adjusted by changing the resistance and lay-out of several voltage divider resistors (range:500mV-2600mv).

Variables:

Table 32 Variables in Signal generation sub-system test

Nr.	Property	Vary/Measure	Value	Unit
1	Power from Arduino	Vary	5.0	V
2	Frequency	Vary	50-3600	Hz
3	Differential voltage	Measure	500-2600	mV
4	Error	Measure	0-6%	%
5	Stability	Measure	\	\

Testing tools:

Table 33 Testing tools in Signal generation sub-system test

Nr.	Item	Demands
1	Laptop	\
2	Connecting cable (USB Micro B)	\
3	Oscilloscope (DSO5202P)	\
4	Mobile phone	Photography and video
5	Jumper cables	\
6	Breadboard	\
7	Arduino Uno board	\
8	Resistors	Several with different resistance

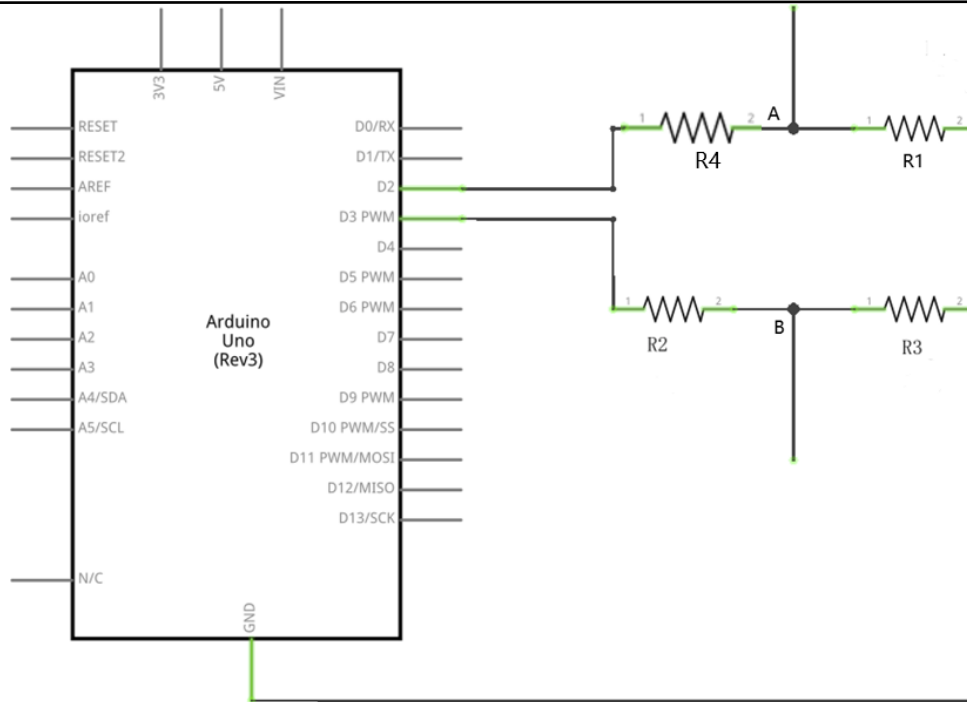


Figure 100 Signal generation circuit schematics

Method:

1. Layout several (3-4) resistors reasonably on breadboard to configure the output voltage of Arduino board.
2. Connect Arduino Uno board with laptop, enabling Arduino board as power supply.
3. Make physical connections between Arduino Uno board with the resistor layout.
4. Connect the oscilloscope (Channel 1/2) to the to port A and B in the circuit.
5. Upload code into Arduino Uno board and observe the display of oscilloscope.
6. Change the frequency (50Hz—3600Hz) of square wave and take down the data on the oscilloscope.
7. Replace the resistors with other resistances and repeat step 5-6.
8. Record and organize the measuring results collected.
9. Disconnect all wires and organize devices and instruments.

Test results

In this test, there are 4 group resistors combination tested in total, which means 4 different amplitude of AC square waves were generated and its properties are tested. The test layout diagram and data tables are displayed below.

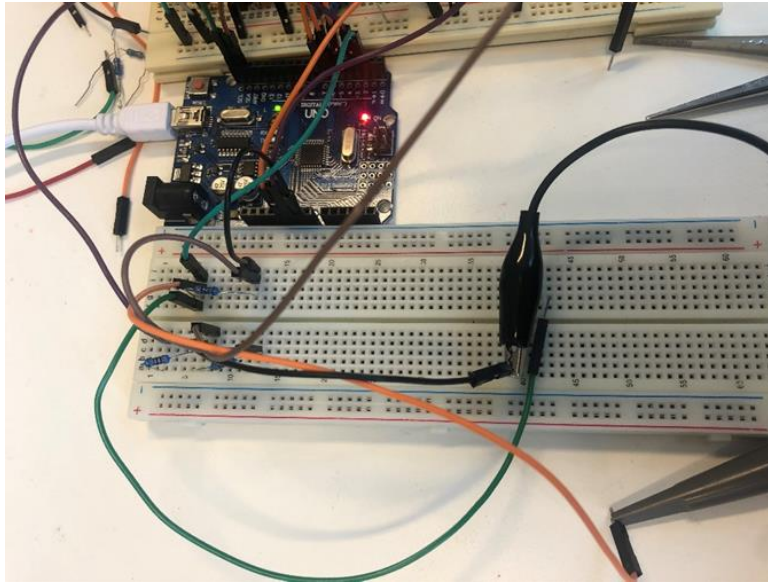


Figure 101 Signal generation subsystem test diagram

Table 34 Signal generation group1

Nr.	Frequency set	Frequency	Minimum(mV)	Maximum(mV)	Error
1	50	49.7	-780	880	0.60%
2	100	99.4	-780	880	0.60%
3	200	198.4	-780	880	0.80%
4	300	297	-780	880	1.00%
5	500	493	-780	880	1.40%
6	800	786.1	-780	880	1.74%
7	815	800.1	-780	880	1.83%
8	1000	978.4	-780	880	2.16%
9	1500	1461.5	-780	880	2.57%
10	2000	1938	-780	880	3.10%
11	3000	2873	-780	880	4.23%
12	3600	3401.5	-780	880	5.51%

Table 35 Signal generation group2

Nr.	Frequency set	Frequency	Minimum (mV)	Maximum (mV)	Pulse Width(us)	Error
1	50	49.67	-820	780	10.01ms	0.66%
2	100	99.3	-820	780	5.030ms	0.70%
3	200	198.4	-820	780	2.520ms	0.80%
4	300	297.2	-820	780	1.684ms	0.93%
5	500	493.3	-820	780	1.014ms	1.34%
6	800	786.1	-820	780	633	1.74%
7	815	801.2	-820	780	621	1.69%
8	1000	978	-820	780	508	2.20%
9	1500	1458.5	-820	780	342	2.77%
10	2000	1934	-820	780	257	3.30%
11	3000	2861	-820	780	173	4.63%
12	3600	3407	-820	780	145	5.36%

Table 36 Signal generation group3

Nr.	Frequency set	Frequency	Minimum (V)	Maximum (V)	Pulse Width(us)	Error
1	50	49.68	-1	1.84	10.01ms	0.64%
2	100	99.3	-1	1.84	5.040ms	0.70%
3	200	197	-1	1.84	2520	1.50%
4	300	297.2	-1	1.84	1686	0.93%
5	500	493.5	-1	1.84	1014	1.30%
6	800	786.4	-1	1.84	633.2	1.70%
7	815	799.5	-1	1.84	621.2	1.90%
8	1000	978	-1	1.84	508.4	2.20%
9	1500	1459	-1	1.84	341.6	2.73%
10	2000	1934	-1	1.84	256.4	3.30%
11	3000	2863.5	-1	1.84	172.8	4.55%
12	3600	3408	-1	1.84	144.4	5.33%

Table 37 Signal generation group4

Nr.	Frequency set	Frequency	Minimum (mV)	Maximum (mV)	Pulse Width(us)	Error
1	50	49.9	-2600	2640	10.01ms	0.20%
2	100	99.6	-2600	2640	5.030ms	0.40%
3	200	198.4	-2600	2640	2.520ms	0.80%
4	300	297.6	-2600	2640	1.684ms	0.80%
5	500	490.1	-2600	2640	1.014ms	1.98%
6	800	781.2	-2600	2640	633	2.35%
7	815	801.2	-2600	2640	621	1.69%
8	1000	977.5	-2600	2640	508	2.25%
9	1500	1466	-2600	2640	342	2.27%
10	2000	1919	-2600	2640	257	4.05%
11	3000	2868	-2600	2640	173	4.40%
12	3600	3436	-2600	2640	145	4.56%

As mentioned earlier, totally four combinations of bleeder resistors had been tested and so there are four amplitudes (800mV, 830mV, 1.84V and 2.6V), of which the test results are listed above. When fixing the resistance of voltage divider resistors, which means the amplitude is determined, the error between the frequency set of code in Arduino IDE and actual frequency detected by oscilloscope (reference tool) increases as the frequency value goes up. The errors analysis line chart is as show below.

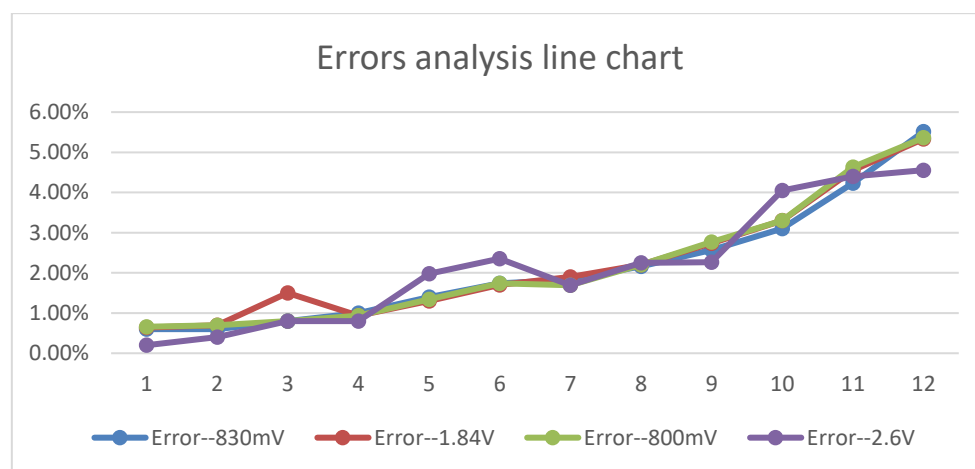
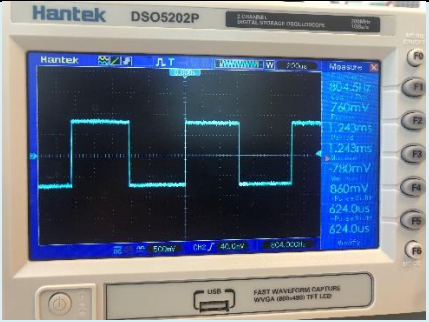
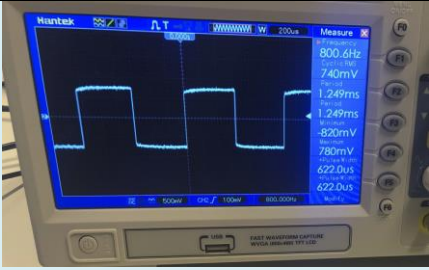
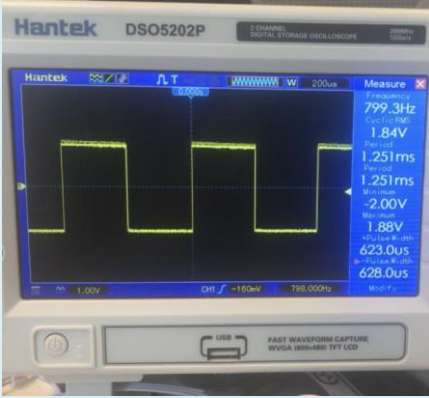
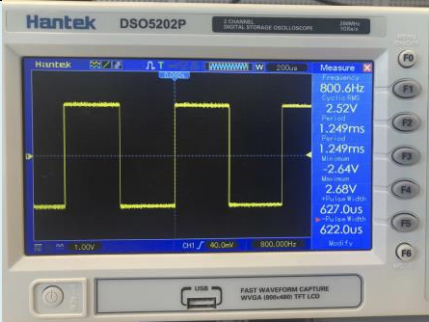


Figure 102 Line chart analysis of signal generation sub-system test

It can be derived from the line chart that within the frequency range (50Hz—3600Hz), the errors are all lower than 6%, which is the expected error maximum, despite of that the error keeps rising trend with the increase of frequency. In the whole system design, 800Hz is determined to be adopted for the frequency of voltage & current system circuit in terms of the previous research of in-company colleague Mick and fellow students. Besides, considering there is relatively much load in the electrode-switch sub-system, large amplitude is more feasible for the entire system design.

Table 38 Test results displayed in oscilloscope and the related parameters

Image of AC square waves	Cyclic Vrms (mV)	Voltage amplitude (mV)	Frequency (Hz)
	760	820	804.5
	740	800	800.6
	1840	1940	799.3
	2520	2660	800.6

Test code:

```
double Frequency = 815;  
double t1=1000000/(Frequency*2);  
double t2=1000/(Frequency*2);
```

```
void setup() {  
  pinMode(2, OUTPUT);  
  pinMode(3, OUTPUT);  
}
```

```
void loop() {  
  if (Frequency >=200){  
    digitalWrite(3, HIGH);  
    digitalWrite(2, LOW);  
    delayMicroseconds(t1);  
    digitalWrite(2, HIGH);  
    delayMicroseconds(t1);  
  }  
  else {  
    digitalWrite(3, HIGH);  
    digitalWrite(2, LOW);  
    delay(t2);  
    digitalWrite(2, HIGH);  
    delay(t2);  
  }  
}
```

Conclusion:

It can be derived that from the data measured in the tables and the figures shown that it is feasible to use the combination of Arduino board and some voltage divider resistors to generate equivalent stable AC square waves and the frequency and amplitude of voltage is also adjustable, which are from 50Hz to 3600Hz and from 700mV to 2.6V respectively. The error between the frequency set in Arduino IDE code and actual frequency increases gradually with the growth of the frequency, but all of the error is under 6%, meeting expected standards.

Voltage & Current measuring sub-system test plan:

Aim:

The aim of voltage & current measuring sub-system test is to confirm that with the AC square waves as power supply of resistors, whether the current flowing through the resistor to be measured and the voltage across the resistor could be detected and measured by ADS1115 in the circuit successfully or not.

Hypothesis:

If the component analog-to-digital converter ADS1115, which serves as the voltage sensor here, could derive the corresponding values (voltage of the reference resistor and the resistor to be tested) from circuit to be measured, the system would pass the test.

Variables:

Table 39 Variables in Voltage & Current measuring sub-system test

Nr.	Property	Vary/Measure	Value	Unit
1	Power from Arduino	Vary	5.0	V
2	Frequency	Vary	800	Hz
3	Amplitude of AC square wave	Vary	2.4	V
4	Voltage across resistor	Measure	0-1600	mV
5	Error	Measure	0-6%	%
6	Stability	Measure	\	\

Testing tools

Table 40 Testing tools in Voltage & Current measuring sub-system test

Nr.	Item	Remark
1	Connecting wire (USB Micro B)	\
2	Arduino Uno board	\
3	Resistors	100Ω, 270Ω, 510Ω, 2000Ω
4	ADS1115	Analog-to-Digital Converter
5	Breadboard	\
6	Jumper cables	Several
7	Laptop	Power for Arduino
8	Mobile Phone	Photography and video
9	Oscilloscope	\
10	Signal generation sub-system	\

Method:

1. Connect Arduino Uno with laptop.
2. Connect Arduino Uno with voltage sensor (ADS1115) corresponding ports.
3. Connect the signal generation sub-system with measuring sub-system side.
4. Reasonably layout 270Ω testing resistor connected to optocoupler.
5. Upload the Arduino IDE code into Arduino board and open serial monitor.
6. Observe and take down the results displayed in IDE serial monitor.
7. Change the resistance of the testing resistor to 510Ω.
8. Repeat step 5-6.
9. Change the resistance of the testing resistor to 2000Ω.
10. Repeat step 5-6.
11. Record all the data connected and make comparison table.
12. Disconnect wires and organize the devices and testing tools.

Expected results:

With optocoupler included in the circuit, voltages of the reference resistor and testing resistor can still be detected and measured. No matter how much resistance of the testing resistor is, the test error is under 6%.

Test results

Table 41 Test for 270Ω resistor

Nr.	Voltage of ref (mV)	Voltage (mV)	Resistance (Ω)
1	75.58	1531.45	2010.15
2	75.58	1530.7	2009.17
3	75.58	1531.07	2009.66
4	75.58	1531.45	2010.15
5	75.58	1531.07	2009.66
6	75.58	1531.26	2009.91
7	75.58	1531.23	2009.87
8	75.6	1531.27	2009.39
9	75.58	1531.26	2009.91
10	75.59	1531.22	2009.59

Table 42 Test for 510Ω resistor

Nr.	Voltage of ref (mV)	Voltage (mV)	Resistance
1	290.67065	790	269.62
2	290.67065	786	268.26
3	286.70245	790	273.36
4	289.6786	788	269.86
5	288.68655	790	271.48
6	290.67065	790	269.62
7	287.6945	786	271.03
8	286.70245	785	271.63
9	285.7104	784	272.22
10	289.6786	788	269.86

Table 43 Test for 2000Ω resistor

Nr.	Voltage of ref (mV)	Voltage (mV)	Resistance
1	257.933	1326.0	510.00
2	257.933	1323.0	508.85
3	255.9489	1320.0	511.63
4	253.9648	1315.0	513.67
5	256.94095	1320.0	509.65
6	257.933	1324.0	509.23
7	255.9489	1321.0	512.02
8	254.95685	1320.0	513.62
9	254.95685	1326.0	515.95
10	258.92505	1323.0	506.90

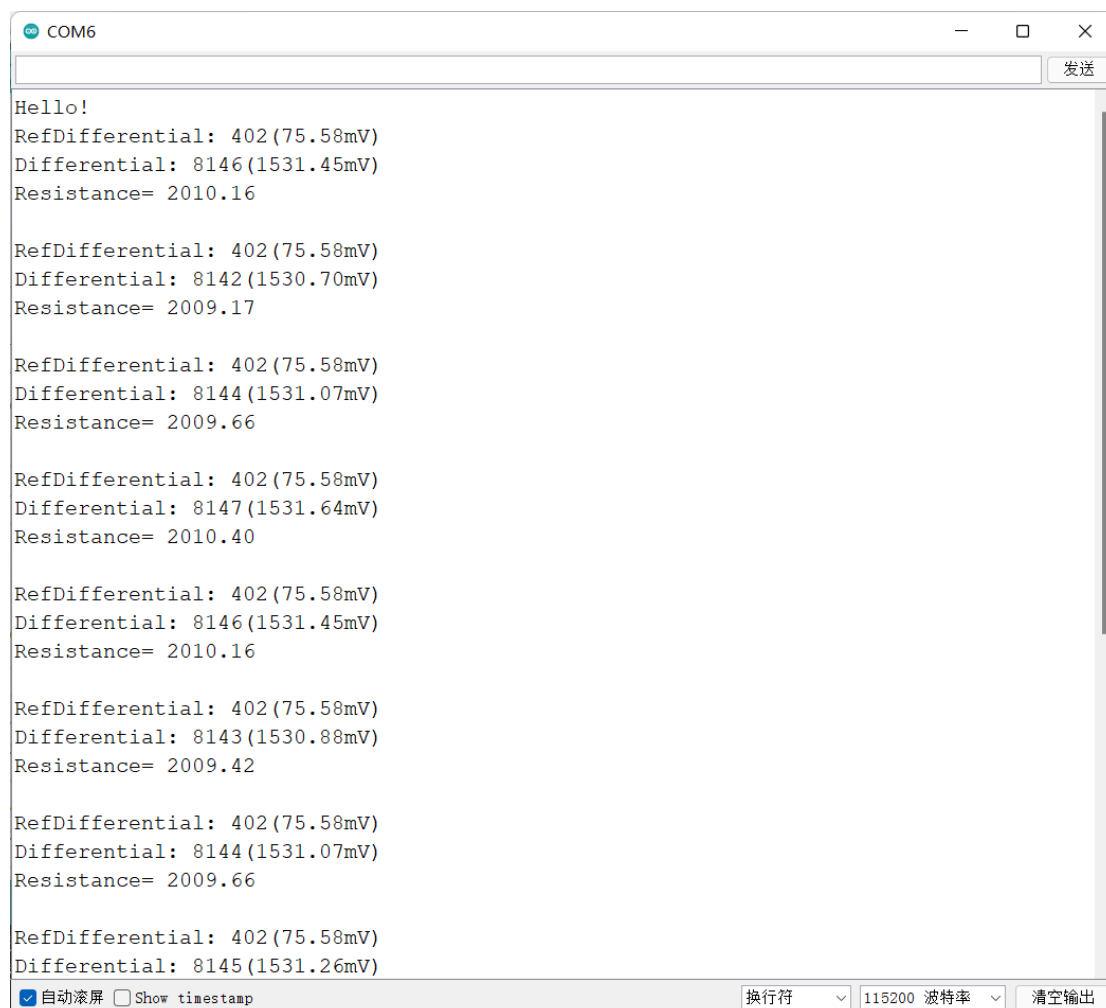


Figure 103 Screenshot of Arduino IDE serial monitor when testing

Test code:

```
#include <Wire.h>

#include <Adafruit_ADS1X15.h>

Adafruit_ADS1115 ads1115;

void setup() {
  Serial.begin(115200);
  Serial.println("Hello!");
  ads1115.begin();
  pinMode(5, OUTPUT);
}

void loop() {
  int16_t results1;
  int16_t results2;
  double I_results1;
  double b=0,a=0,resistance=0;

  digitalWrite(5, HIGH);
  delay(100);
  results1 = ads1115.readADC_Differential_0_1();
  I_results1 = results1 * 3/99.2;
  results2 = ads1115.readADC_Differential_2_3();
  delay(2000);

  digitalWrite(5, LOW);
  delay(100);
  results1 = ads1115.readADC_Differential_0_1();
  b=abs(results1);
  Serial.print("RefDifferential: "); Serial.print(results1); Serial.print("("); Serial.print(results1 * 0.188);
```

```
Serial.println("mV");

results2 = ads1115.readADC_Differential_2_3();

a=abs(results2);

Serial.print("Differential: "); Serial.print(results2); Serial.print("("); Serial.print(results2 * 0.188);
Serial.println("mV");

resistance = (a/b) * 99.2;

Serial.print("Resistance= "); Serial.println(resistance); Serial.print("\n");

delay(2000);

digitalWrite(5, HIGH);

}
```

Conclusion:

Through the test, conclusion can be obtained that the existence of optocoupler in the circuit does not influence the voltage measurement of resistors executed by ADS1115. For voltage & current measuring sub-system, ADS1115 can still relatively accurately measure the voltage across the components with different resistance and transfer the data collected back to Arduino processor. The error analysis is in the thesis text.

ADS1115 test plan:

Tools:

Table 44 Testing tools in component ADS1115 test

Nr.	Item	Remark
1	Connecting wire (USB Micro B)	\
2	Arduino Uno board	\
3	Resistors	100 Ω , 510 Ω , 1000 Ω , 2000 Ω , 5100 Ω
4	ADS1115	Analog-to-Digital Converter
5	Breadboard	\
6	Jumper cables	Several
7	Laptop	Power for Arduino
8	Mobile Phone	Photography and video
9	Oscilloscope	\

Method:

1. Place resistors (100 Ω , 1000 Ω in series) on the breadboard.
2. Connect ADS1115 with Arduino Uno (VCC, GND, SCL, SDA pins).
3. Connect the analog signal port AIN1 and AIN2 of ADS1115 with the upper end of 100 Ω resistor and 1000 Ω resistor respectively.
4. Connect the Arduino with power supply (laptop) and upload the code to ADS1115.
5. Observe and take notes of the values displayed in the Arduino IDE serial monitor.
6. Replace the 100 Ω resistor by 510 Ω and repeat step 3-5.
7. Replace the 510 Ω resistor by 2000 Ω , and place one 5100 Ω resistor on the breadboard, which is in series with the 510 Ω and 2000 Ω resistors.
8. Connect the analog signal port AIN3 with the upper end of 5100 Ω resistor and repeat step 4-5.
9. Switch off the power.
10. Organize devices, cables and components.

Expected results: ADS1115 could measure the voltage of the resistor to be tested within the acceptable error range and transfer the data collected to Arduino processor.

Test results

In fact, this test is to detect the potential of two point to ground, but it can be equally regarded as the measurement of the partial voltage of each resistor. The whole test for ADS1115 can be divided into 3 parts. The first is the measurement for two resistors whose resistances are 100 Ω and 1000 Ω respectively. Secondly, measure partial voltage condition of one other resistor combination. Lastly the partial voltage condition of 3 different resistors was figured out, of which the figure is shown as followed.

1. 100Ω and 1000Ω in series

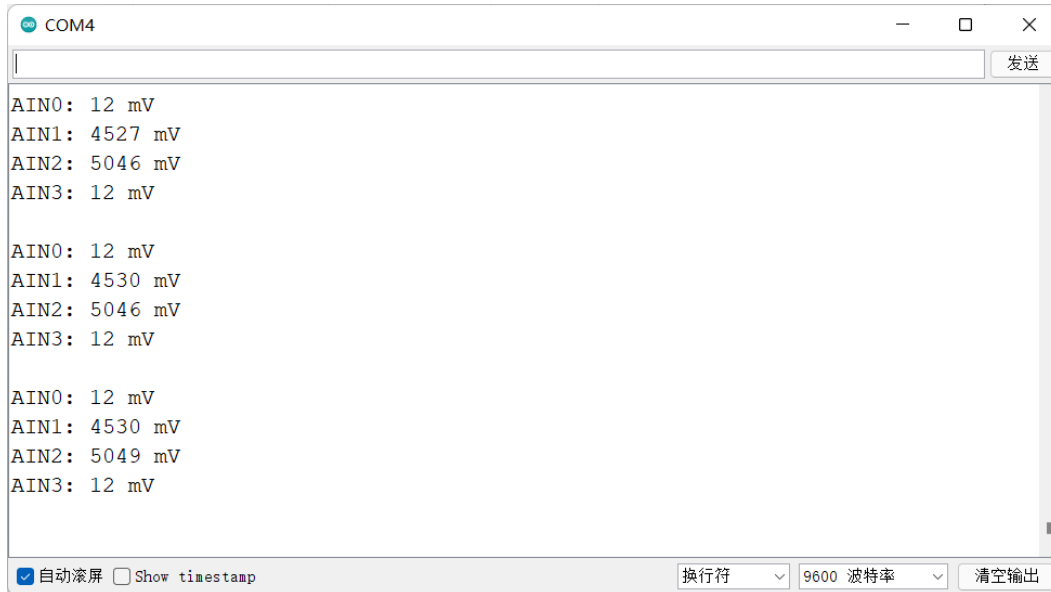
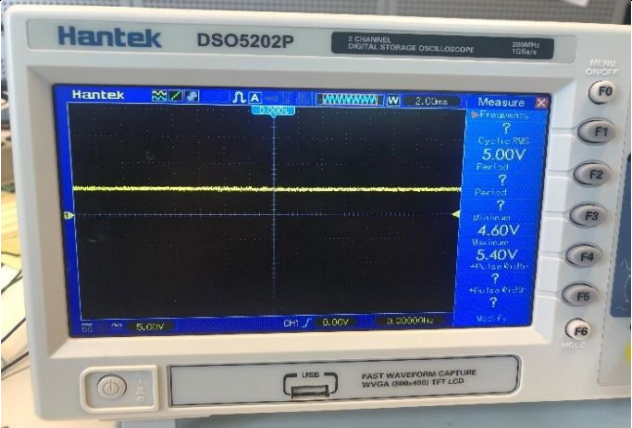
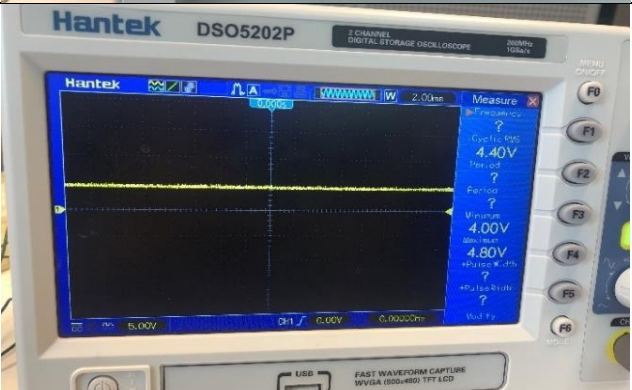


Figure 104 Test results1 displayed in Arduino IDE serial monitor

As shown in the figure above, 3 tests were carried out and now reorganize the data into table below.

Table 45 Test results of 100Ω and 1000Ω in series

Resistor	Voltage in test no.1 (mV)	Voltage in test no.2 (mV)	Voltage in test no.3 (mV)	Voltage detected by oscilloscope
100Ω	5046-4527=519	5046-4530=516	5049-4530=519	
1000Ω	4527	4530	4530	

2. 510Ω and 1000Ω in series

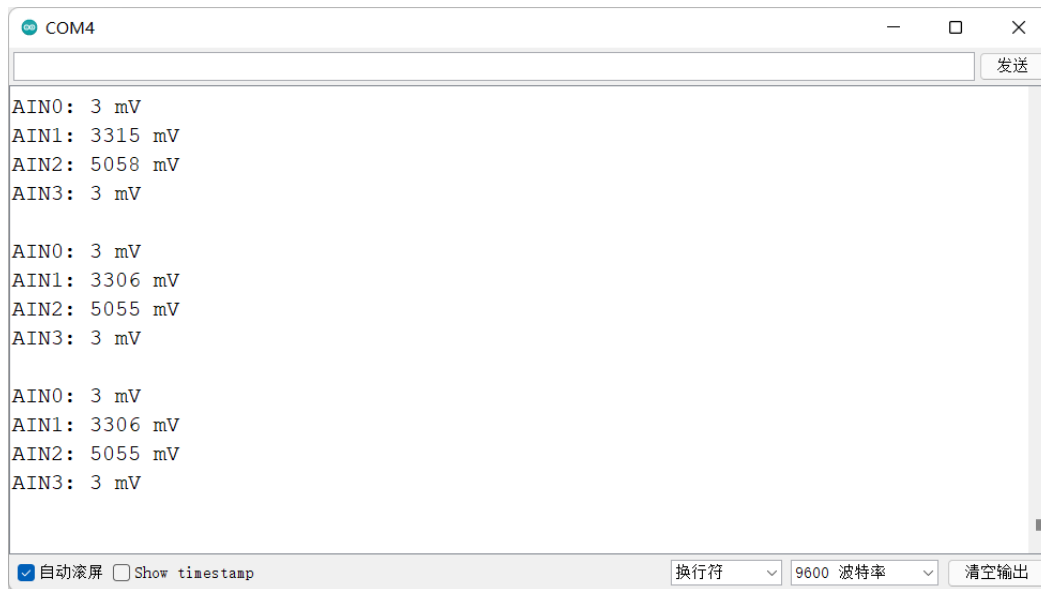
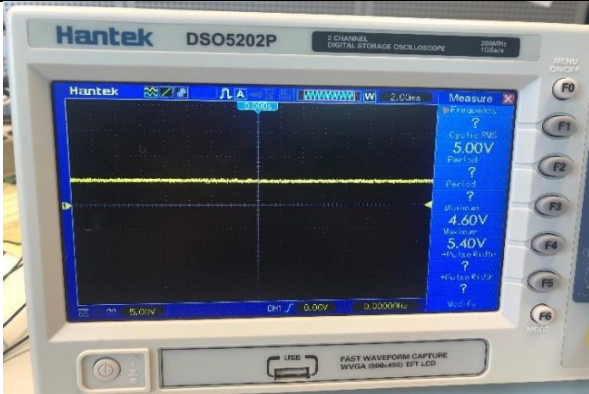
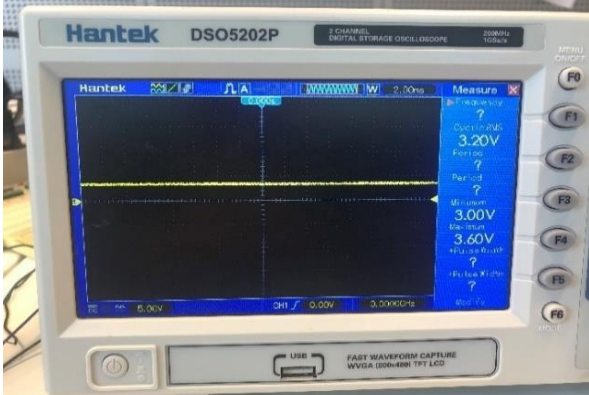


Figure 105 Test results2 displayed in Arduino IDE serial monitor

As shown in the figure above, 3 tests were carried out and now reorganize the data into table below.

Table 46 Test results of 510Ω and 1000Ω in series

Resistor	Voltage in test no.1 (mV)	Voltage in test no.2 (mV)	Voltage in test no.3 (mV)	Voltage detected by oscilloscope
510Ω	5058-3315=1743	5055-3306=1749	5055-3306=1749	
1000Ω	3315	3306	3306	

3. 1000Ω, 2000Ω and 5100Ω is series

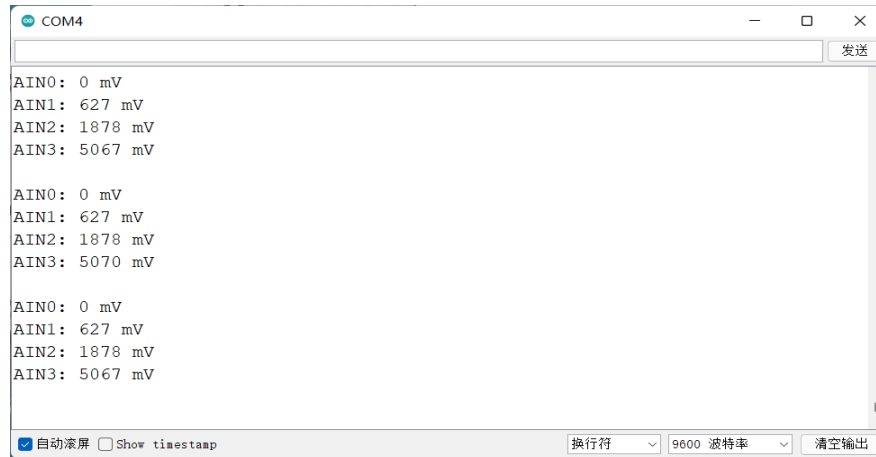
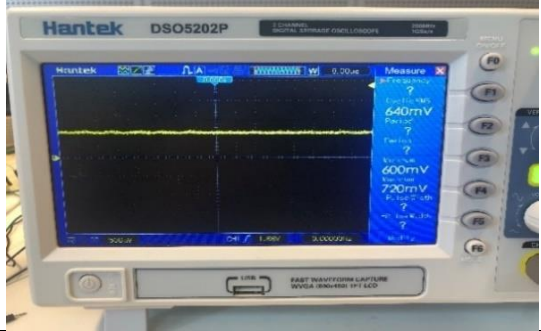
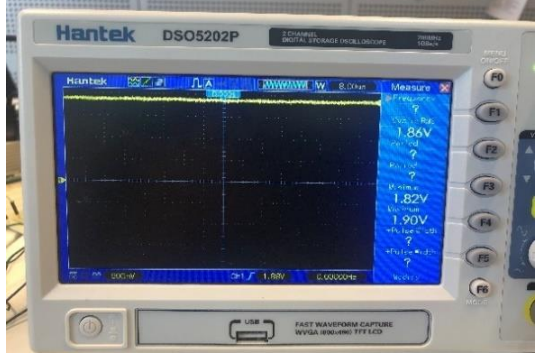



Figure 106 Test results3 displayed in Arduino IDE serial monitor

As shown in the figure above, 3 tests were carried out and now reorganize the data into table below.

Table 47 Test results of 1000Ω, 2000Ω and 5100Ω in series

Resistor	Voltage in test no.1 (mV)	Voltage in test no.2 (mV)	Voltage in test no.3 (mV)	Voltage detected by oscilloscope
1000Ω	627	627	627	
2000Ω	1878-627=1251	1878-627=1251	1878-627=1251	
5100Ω	5067-1878-627=2562	5070-1878-627=2565	5067-1878-627=2562	

Test code:

```
#include <Wire.h>
#include <Adafruit_ADS1X15.h>

Adafruit_ADS1015 ads1015;

void setup(void)
{
  Serial.begin(9600);
  Serial.println("Hello!");

  Serial.println("Getting single-ended readings from AIN0..3");
  Serial.println("ADC Range: +/- 6.144V (1 bit = 3mV)");
  ads1015.begin();
}

void loop(void)
{
  int16_t adc0, adc1, adc2, adc3;

  adc0 = ads1015.readADC_SingleEnded(0);
  adc1 = ads1015.readADC_SingleEnded(1);
  adc2 = ads1015.readADC_SingleEnded(2);
  adc3 = ads1015.readADC_SingleEnded(3);
  Serial.print("AIN0: "); Serial.print(adc0*3); Serial.println(" mV");
  Serial.print("AIN1: "); Serial.print(adc1*3); Serial.println(" mV");
  Serial.print("AIN2: "); Serial.print(adc2*3); Serial.println(" mV");
  Serial.print("AIN3: "); Serial.print(adc3*3); Serial.println(" mV");
  Serial.println(" ");

  delay(1000);
}
```

Conclusion:

By comparing the values measured by ADS1115, which is shown in Arduino IDE serial monitor, and the voltage values displayed in oscilloscope, it can be derived that though there is measuring error, ADS1115 can detect and measure the voltage drop of electronics component. This test proved the function of ADS1115, but the reasonableness of the measured values cannot be proven.

TLP521-4 test plan:

Tools:

Table 48 Testing tools for component TLP521-4 test

Nr.	Item	Remark
1	Connecting wire (USB Micro B)	\
2	Arduino Uno board	\
3	Resistors	100Ω, 1kΩ, 2kΩ, 10kΩ
4	TLP521-4	Optocoupler
5	Transistor	P-N-P type
6	Breadboard	\
7	Jumper cables	Several
8	Laptop	Power for Arduino
9	Mobile Phone	Photography and video
10	Multimeter	\

Method:

1. Reasonably place one TLP521-4 chip on the center of breadboard.
2. Connect 2kΩ pull-up resistors with TLP521-4.
3. According to the schematic diagram, finish the rest circuit including transistor and 100Ω test resistor connected to 5V of Arduino.
4. Connect the TLP521-4 with digital port 2 of Arduino board.
5. Compile and upload the code into TLP521-4.
6. Use the multimeter to measure the potential of the 100ohm test resistor.
7. Observe and take notes of the data on the screen.
8. Disconnect the power and relations of each component.
9. Organize all devices and instruments.

Expected results: When digital pin2 is set at high level, the optocoupler TLP521-4 would not work, which lead the output pins of it are all open. In this case, this is no voltage drop through the test resistor. On the contrast, when digital pin2 is set at low level, the optocoupler TLP521-4 would work normally, which lead each set of output pins is closed. In this case, this is voltage drop (should be almost 5V) through the test resistor.

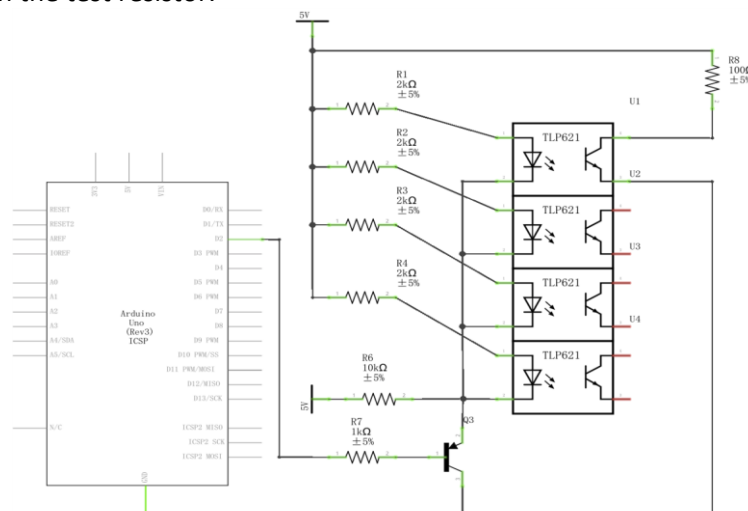


Figure 107 TLP521-4 test circuit schematics

Test results

See from the figures below, on the left side, using multimeter to derive that the potential to ground of the lower end of 100 Ω resistor is about 4.91V, almost at 5V (Arduino output), which represents that the optical coupler TLP521-4 keeps switched off. After setting the potential of digital pin 2 at low level, of Arduino Uno, the TLP521-4 switched on and then there is current throw the 100 Ω resistor. Correspondingly, the potential to ground of the lower end of 100 Ω resistor turned to be 0.117V, almost 0V, the reason for this is there is internal resistance of the transistor (switch) inside the optocoupler TLP521-4.

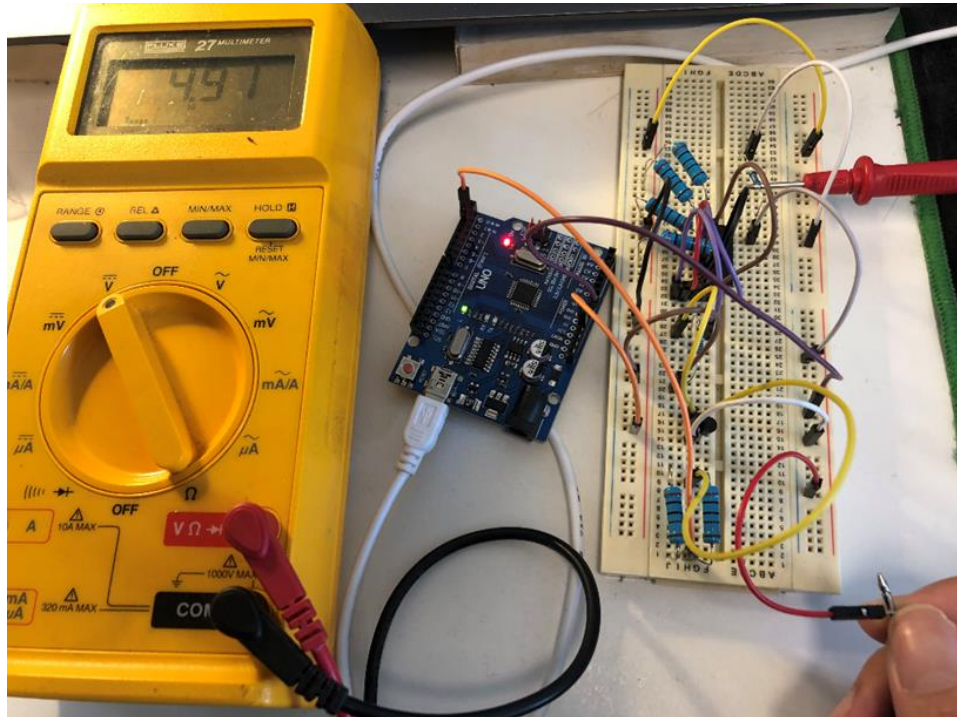


Figure 108 Testing diagram1 in TLP521-4 test

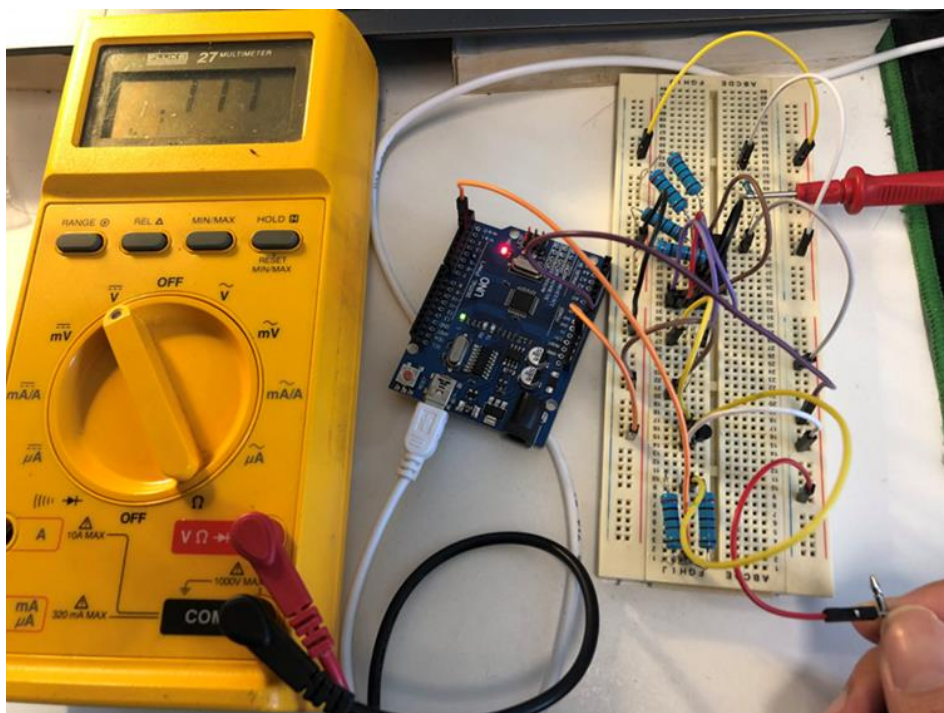


Figure 109 Testing diagram2 in TLP521-4 test

Test code:

```
void setup() {  
  pinMode(2, OUTPUT);  
  
}  
void loop() {  
  digitalWrite(2, LOW);  
  delay(3000);  
  
  digitalWrite(2, HIGH);  
  delay(3000);  
  
}
```

Conclusion:

The test proved that the optocoupler TLP521-4 can be controlled by setting the potential of digital pin of Arduino board manually and the switch function of it can execute successfully. In a word, each TLP521-4 can be used as a timer switch by coding in Arduino IDE.