A Variable Load Emulator with a Digital Control Interface

XJME3890 Individual Engineering Project
A Variable Load Emulator with a Digital Control Interface
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SCHOOL OF MECHANICAL ENGINEERING

UNIVERSITY OF LEEDS

XJME3890	Individual Engineering Project

TITLE OF PROJECT

A Variable Load Emulator with a Digital Control Interface

PRESENTED BY

Yuhui Bi

If The Project Is Industrially Linked Tick This Box
And Provide Details Below

Company Name and Address:

This project report presents my own work and does not contain any unacknowledged work from any other sources.

Signed 毕宇辉 Yuhui Bi Date: 13 May 2021

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Abstract

With rapid development of integrated circuit, the application and invention of electronic devices tend to soar. The typical device, electronic load, applies to engineering.

The variable load emulator (based on the electronic load) is capable to emulate resistance and capacitance as desired by users so that it can be utilised to evaluate and determine the performance of power sources.

This project is based on the integration of simulation and real electrical circuit. The aims are to build a variable load emulator with the function of digital control, including some objectives, such as simulation, analysis of basic theory, building of real circuit, collection of data, analysis on error, future work and so forth.

The function of digital control is implemented by receiving and sending signal by Microcontroller Unit so that electronic load can be controlled as desired by a digital interface from LabVIEW interface. The theory is based on binary. Every digit of corresponding binary number represents the condition of each I/O of Microcontroller Unit. Relays connect with electronic loads to achieve partial close circuit as desired.

The variable load emulator was implemented. It had many merits such as easy to control and no requirement of feedback. It can receive data and emulate resistance as desired. The output range of resistance varied from 0 to 65k ohms.

After experiments, the relative error is high (>1%) when emulating low resistance (≤128 ohm). It is acceptable (<1%) when emulating medium or high resistance (>128 ohm).

Nomenclature

Frequently used:

AC: Alternating Current

B: Base Pin of Transistors

C: Collector Pin of Transistors

COM: Serial Interface

DC: Direct Current

E: Emitter Pin of Transistors

GND: Ground

I/O: Input/ Output Port

MCU: Microcontroller Unit

MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor

NO: Normally Open (One Condition of Relays)

NPN: A Common Type of Transistors

PC: Personal Computer

PNP: A Common Type of Transistors

VCC: Voltage Current Condenser

VISA: Virtual Instruments Software Architecture (Telecommunication package of LabVIEW)

Not commonly used:

AD: Analog to Digital Convert

AWG: American Gauge Wire

BJT: Bipolar Junction Transistor

C_i: Capacitance of each Capacitor

C_T: Total Capacitance

Class E: Class E Amplifier (Used at Radio Frequencies)

CPU: Central Processing Unit

DA: Digital to Analog Convert

EEPROM: Electrically Erasable Programmable Read-Only Memory

GTR: Giant Transistor

HMI: Human-Machine Interface

IGBT: Insulated Gate Bipolar Transistor

I-V Curve: Current-Voltage Curve

MPCC: Model Predictive Current Control

PCB: Printed Circuit Board

PID: Proportional–Integral–Derivative Controller

P-V Curve: Power-Voltage Curve

R_i: Resistance of each Resistor

R_T: Total Resistance

RS-232: Serial communication Transmission Standard in Telecommunication

RST: Abbreviation of Reset

SEIG: Self Exited Induction Generator

SRAM: Static Random-Access Memory

UPS: Uninterruptible Power Supply

VSI: Voltage Source Inverter

XTal: Clock Frequency of Crystal Oscillator

ZVS: Zero Voltage Switch

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Chapter 1：Introduction

1.1 Introduction

With the rapid development of integrated circuit and microelectronic technology, the invention and application of electronic devices tend to soar year by year. The typical electronic device, power source applies to the fields of engineering, science, education, and so forth. Before manufacturing, it is mandatory to conduct dynamic experiments for long time so that the performance of power sources can be evaluated and determined. The conventional one, sliding resistor cannot be used anymore for many demerits such as unrecyclable energy (Liu, 2018).

Electronic load emerges under such background. Electronic load can emulate resistance or capacitance as desired. Electronic load can simulate the real load of power electronic devices and main features of various types of loads. It owns advantages such as convenient adjustment, high precision (Xu, 2012).

Manufacturers and engineers connect electronic load with tested power source to observe the characteristics of power, such as I-V curves. A typical example is that photovoltaic arrays characteristic test technology is based on it. A novel electronic load device can be used in the investigation process for data logging and plotting I-V, P-V curves (Al Ameri et al., 2009; Feng et al., 2011).

It is worthwhile to develop a variable load emulator that is easy to control and maintain, and to emulate electronic load to test the performance of power sources.

In this project, the programmable controlled electronic load (described as variable load emulator) involved 16 resistors and 8 capacitors. LabVIEW windows were used as the principal computer interface (described as digital control interface). The Microcontroller Unit (MCU), STC89C52 was taken as slave computer to receive data transmitted from PC via serial interface (COM). The codes of C language were recorded in the chip of MCU in advance. The main feature of MCU is to output high or low voltage level (electrical signal) from every I/O (Input/Output Port) as required. The desired electronic load can be obtained by introducing relay modules. Finally, the function of variable load can be achieved by causing short circuit on partial resistors and open circuit on partial capacitors.

There are some merits about this project, such as high precision (medium and high resistance), no requirement of feedback, high safety, difficult to damage and easy to maintain, difficult to lose control.

1.2 Aim

The aim of the project is to develop a variable load emulator with a digital control interface. It involves simulation and real circuit. Also taken account is to investigate the difference between ideal resistance and real one and a series of optimizations. Ideally, the maximum output for resistance and capacitance are 65535Ω and 255μF.

1.3 Objectives

The final purpose is to input the desired resistance or capacitance on PC and transmit data to MCU via serial interface and transfer the corresponding signal to each I/O of MCU so that desired circuit can be connected. The complex process can be dissolved as followed steps:

1) Draw the schematic simulation diagram on Proteus software.
2) Create a control interface on LabVIEW software.
3) Write codes of C language that is used to control the MCU on Keil software.
4) Build the real electrical circuit with combination of realy modules.
5) Investigate and minimize the relative error.
6) Optimize and improve the design.

Schematic diagram for real circuit can be found below on fig 1.3.1.

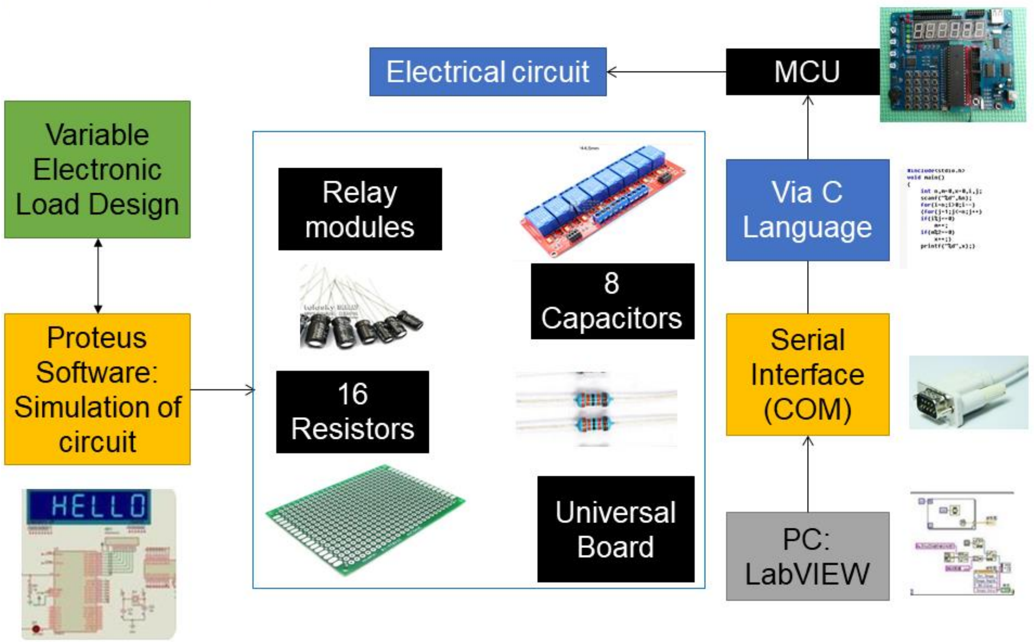

Fig 1.3.1: Schematic diagram for real circuit

1.4 Project report layout

This report is organised as follows:

Chapter 1: Introduction: It includes comprehensive introduction, aims and objective of this project, which are described above.

Chapter 2: Literature Review: It contains introduction to electronic load, background, research history. Patent & application and future development trend are proposed.

Chapter 3: Basic Knowledge and Conceptional Analysis: Relative knowledge, such as binary, analogic signal, MCU, and how the system works are described.

Chapter 4: Conversion to Real Application: This chapter introduces real electronic application. The function of digital control is achieved. A final product can be finished.

Chapter 5: Experimental Data and Discussion. Experimental data are collected and analysed. The sources of error and solutions are addressed and a series of optimizations and imrpvements are also proposed.

Chapter 6: Conclusion: Conclusion, discussion and achievements are addressed. Fututre work to improve this project is also introduced.

Chapter 7: Reference: A number of thesis, journal articles, websites are referenced.

Chapter 2：Literature Review

2.1 Introduction to Electronic Load

A general electronic load is an electronic device that controls the flux through MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) or transistor, depending on the power tube that consumes electrical energy. It is usually capable of dynamic loading, and frequently programmable or computer controlled. It is utilised to simulate the real load of power electronic devices. It can simulate the main characteristics of capacitive load, resistive load, inductive load and mixed load with different values. By adjusting the load size, the load voltage can be accurately detected, and the load current can be accurately adjusted. At the same time, the short circuit, overcurrent and dynamic properties of the load can be simulated, and some characteristics of the nonlinear load can also be simulated.

Electronic load has the advantages of strong generality, convenient adjustment, good stability and high precision, and it leads the development of power test load. Generally, manufacturers who is more stringent for requirement of power supply will use electronic load to detect the quality of the power supply (Xu, 2012).

There are four common types of electronic load: Benchtop Electronic Load, Slot Electronic Load, System Electronic Load and Modular Electronic Load. Seven common measurement types can be implemented: they are voltage, current, peak-current, frequency, crest-factor, power-factor and true power (Sunpower, 2019).

There are three modules on the electronic load in laboratory. Every module can work independently with 3 independent working modes, namely, constant current mode, constant voltage mode and constant resistance mode (Liu& Hao, 2018).

2.2 Background

Nowadays, the technology of electronic power has developed rapidly, and the number of high-power electrical appliances is increasing gradually. Electrical and electronic equipment must conduct different kinds of technical index and performance test experiments (a variety of tests for 24 ~ 72 hours normally) and reach the national standard criteria (like GB in China, or BS in the UK), then it can be manufactured by industries and used by consumers. The tests include reliability test (aging discharge test), output characteristic test, and so forth. Power performance has different properties, and it is often necessary to access parameters of different properties when testing. The traditional power supply performance testing methods cannot meet the requirements of constant current, constant voltage. Besides, the aging and burnout may happen under the environment of using for long time with high current, and the electrical energy is dissipated, causing huge waste. To be precise, in the test of AC/DC power performance, the load needs to be tuned, and the traditional sliding resistor is not convenient to use for great limitations, such as the large volume of the high-power variable resistor and the discontinuous resistance value of the separation resistor (Pan, 2003; Fu, 2017; Liu, 2018).

Electronic load can save energy and is smaller in size with more efficiency than conventional resistance load. Therefore, electronic load is generally utilised in the field of power, communication, automobile, accumulator, and so forth (Ding, 2008).

2.3 Research History and Classification of Electronic Load

The research on electronic load is tough. It underwent the change on little power, high power, Bipolar Junction Transistor (BJT), Metal-Oxide-Semiconductor Field-Effect Transistor (MOSEFT, as shown on figure 2.3.1) and finally to Insulated Gate Bipolar Transistor (IGBT). After years of research and development, the latest product, IGBT has integrated the advantages of GTR (Giant Transistor, or called as Power BJT) devices and MOSFET, which also makes it own the advantages of high input impedance, low saturation voltage, simple driving circuit, low driving power, good thermal stability and so forth (Liang, 2020). It can discharge by controlling flux.

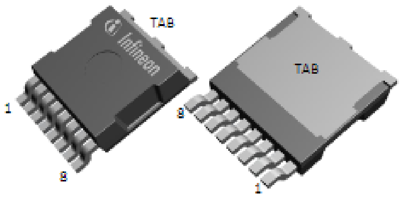

Figure 2.3.1: MOSFET product of Infineon (2021)

There are some reliable international brands of electronic load, such as Agilent and NH Research (as shown on figure 2.3.2) in the USA, Chroma and ITECH in Taiwan of China as well as Faith and Soaring in Mainland China (Liu, 2018).

Figure 2.3.2: Various DC electronic load of NH Research (2021)

As main carrier of STM32 programmable DC electronic load, MOSFET has 2 operating states: switch and linear (Fu, 2017). At present, the main devices used to consume power in DC electronic load are high-power triodes and MOSFET, and the latter one is widely used in commercial electronic loads as power consumption component (Mo et al., 2014). Some auxiliary products associated with the electronic load emerge. For instance, single-switch inverters for variable electronic load modulation operation were design by Roslaniec et al. (2005). It enables rapid synthesis of class E Power Amplifier and maintain ZVS (Zero Voltage Switch) operations over a wide range of resistive loads.

2.4 Significant Applied Field: Programmable Controlled Electronic Load

It is essential to have various operating modes of electronic load. Currently, a host of brands of electronic load have programmable controlled function (Liu& Hao, 2018). Figure 2.4.1 shows DC programmable controlled electronic load product of ITECH.

Figure 2.4.1: DC programmable controlled electronic load product of ITECH (2018)

Programmable controlled electronic load is electronic device that is controlled by programming to tune the value of resistance and consume power. It can measure the load voltage, tune the load current precisely. It can be controlled in a manner to emulate a variety of load characteristics, such as programmable power factor and nonlinear and transient load behaviour, that resemble a real-life electrical load.

Equipment that potentially benefits from testing with programmable controlled electronic load includes the following: generators, Uninterruptible Power Supplies (UPS), transmission lines, and so forth. A novel programmable controlled electronic load based on a hybrid five-level Voltage Source Inverter (VSI) to emulate a variety of static load behaviors, such as resistance, capacitance and inductance loads, high-frequency harmonic loads, and unbalanced loads was developed by Geng et al. (2018). Dynamic load behavior, for instance, modulation loads, can also be achieved.

In this project, codes of C language will be stored in the chip of MCU in advance to achieve the function of programmable controlling. Therefore, inputting resistance or capacitance value on PC, the electronic load can be acquired as desired.

2.5 Application and Patent about Electronic Load

In the test of AC/DC power supply, the load needs to be changed continuously. The traditional sliding resistor is not convenient due to low efficiency, which is only used in teaching of physics lessons in middle school. Using MSP430 (MCU product of Texas Instrument) as the control core, power triode as the controlled object, through the combination of AD/DA hardware control and PID software, the programmable control of DC electronic load and constant current source, which improves the efficiency of AC/DC power parameter test, were realised (Xu, 2013).

Electronic load is widely utilised in photovoltaic application. The variable electronic load is controlled by MCU to conduct real-time synchronous tests in the application of multi-channel photovoltaic module test system (Yan et al.,2018).

MOSFET is used as a nonlinear variable resistance because it has the voltage-resistance controlled characteristics. Along with the usage of high-speed A/D sampling and digital processing modules, I-V characteristic curves of photovoltaic array can be tested (Feng, 2011).

Another typical application is energy feedback electronic load. It is characterized by both using power electronic transformation technology to simulate all kinds of load characteristic, implementation of power testing capabilities, and measurement of the output of the power supply that will be giving back to the electricity grid, recycling to save precious energy. The test process does not generate a large amount of heat, which can avoid the problem of excessively high ambient temperature in the laboratory (Xu, 2012).

Nowadays, numerous patents emerge in society regarding programmable controlled electronic load from companies, institutes, and so forth. For example, a programmable controlled electronic load which is utilised to serve as relay protection device in power system technology application was invented by engineers in State Grid Corporation of China. It can achieve automatic adjustments, adjust step size calibration and own high resistance value precision (Zhang et al., 2013). In addition, a programmable controlled electronic load device that is capable of generating voltage output, also relates to a test method for such an electronic load device to treat the measured object was also invented by engineers. It includes load power unit, control unit, sampling unit as well as voltage output unit (Anon, 2018). Apart from that, it also applies in institutes' teaching. A utility model relates to a programmable controlled electronic load used to simulate the teaching of electronic technology was invented by teachers at a vocational college. It is composed of voltage controlled current source unit, A/D conversion unit, D/A conversion unit, MCU control unit, keyboard unit and display unit. The programmable controlled electronic load can simulate different value of resistance and capacitance flexibly, and it can be applied to the teaching of analog electronic technology courses, which can replace traditional one and save time and expenditure (Lu et al., 2017).

2.6 Future development trend

The variable electronic load has applied to a host of application in the field of electrical and electronic engineering. It has replaced outdated method of conducting experiment. In the past time, different types of resistors and capacitors were combined together. By contrast, based on new technology, a box containing the variable electronic load is utilised. It saves a host of time and expenditure in industry and polytechnic institutes. There are several merits. It is simple designed and reliable to control and maintain. The cost is cheap to afford. This is the reason why it is worthwhile to research and investigate on this topic. Under such circumstance, there is no doubt that advanced electronic load will reduce large proportion of cost and save technician's precious time. Meanwhile, electronic load tends to be intelligent and applies to multidiscipline.

Stand-Alone Micro-Hydropower Systems based on the Self Exited Induction Generator (SEIG) are popular in developing countries. SEIG has distinct advantages than traditional one. An intelligent electronic load controller for Stand-Alone Micro-Hydropower Systems that is able to maintain stable voltage on the demand side of a 3-phase SEIG supplying varying single-phase consumer loads has been developed by Nel and Doorsamy (2018). A SEIG with electronic load controller used in Stand-Alone

Micro-Hydro Power Generation employing uncontrolled turbines, feeding both static and dynamic load was also developed by Singh et al. (2005). The performance of distributed electronic load controller is improved by Roodsari and Nowicki (2018). It consumes the excess generated power individually by each household and operate as a complementary device for voltage and frequency regulation of the SEIG.

A low-cost programmable high-frequency AC electronic load for battery module diagnosis which possesses energy recycling and portability was invented by Lin et al. (2020). It is composed of MCU, signal capturing circuit, resonant circuit. It can be integrated with HMI (Human-Machine Interface).

MPCC (Model Predictive Current Control) to control a programmable AC load was developed by Akhlaghi and Zolghadri (2020). MPCC has fast dynamic response and it can be a fascinating method for power converters.

Energy recycling continues to attract scientists and engineers' attention. The energy recycling DC electronic load is of great importance at battery production and testing process as energy and electricity can be save if they are injected into grid (Yang et al., 2020). Thus, the programmable controlled electronic load developed by Geng et al. has a dedicated control structure to emulate different load behaviours. It has a detailed compensator design to evaluate the system dynamic performance. The proposed system has isolated active DC links to support multilevel converter topology, and it can either dump the energy to a passive load or recycle the energy back to the utility grid through another Voltage Source Inverter (VSI) (2018).

Moreover, a few scholars and researchers start to investigate and develop on new electronic load due to the current issues, such as measurement precision, overheating, and so forth. New electronic load can overcome current issues that is brought by conventional one, and return the measured electrical power to electrical grid, to achieve the re-utilization. Currently, GBEL series of Soaring in Mainland China (as shown on fig 2.6.1), and BF2000 series of ITECH in Taiwan of China own these preliminary products with energy feedback function (Xu, 2012). Nevertheless, it has demerits, such as large volume resulting in too much room is occupied.

Figure 2.6.1: GBEL-S48/600E energy-saving feedback electronic load of Soaring (2021)

2.7 Microcontroller Unit (MCU)

Microcontroller is an integrated circuit chips to control system or equipment. It is equivalent to a microcomputer system. It integrates the microprocessor, memorizer and various I/O interfaces, including CPU (Central Processing Unit), SRAM (Static Random-Access Memory), I/O port and interrupt system, timer/counter, and so forth. (Wang, 2019). It is wildly utilised in various application by engineers, researchers and students. Table 2.7 lists main MCU products and their merits and demerits.

Table 2.7: Main products of MCU and their merits and demerits

	Affiliated company	Merits	Demerits
51 Series	Intel, STC, ATMEL	Easy to use for beginners, simple peripheral circuits	Little number of registers, slow running speed
STM32	STMicroelectronics	Low power dissipation, high integrated circuit	Difficult to learn for beginners
MSP430	Texas Instrument	Simplified built-in command, high running speed	No protection for I/O, no EEPROM (Electrically Erasable Programmable Read – Only Memory)
AVR	ATMEL	Simplified built-in command, strong ability of anti-jamming	Complex instruction system, no bit operation

Arduino, based on AVR, is popular among college students for ease of operations, as shown on figure 2.7.1. It enables users to create interactive electronic objects. It is an open-source electronic platform based on both hardware and software (2021).

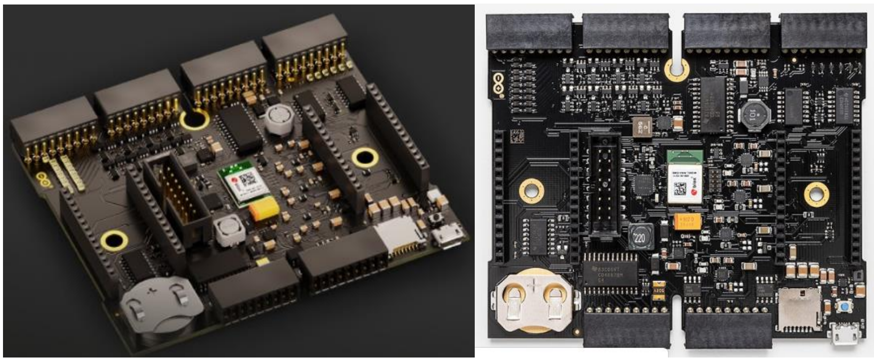

Figure 2.7.1: Arduino (2021) product

STC89C52 (affiliated to 51 Series) is applied in this project for several reasons, ease of operation, perfect centralized management of bus special register, numerous logical bit operation functions and rich control-oriented instruction system (Anon, 2017; Anon, 2020).

2.8 Conclusion

Research and Development on electronic load with high precision is of great importance to engineering technology. Electronic load can be used to evaluate and determine the performance of power source via a series of testing. Programmable controlled electronic load can be used to emulate dynamic load behaviour (Lin et al., 2020). It can solve problem of traditional electronic load, such as high volume and resistance discontinuity. With the development of microelectronics and network technology, digitization, delicate network and high intelligence of electronic load can be achieved (Liu, 2018). It is widely utilized to test various devices such as solar inverters, UPS (Uninterruptible Power Supply), filters, generators and measuring devices (Akhlaghi & Zolghadri, 2020).

Chapter 3：Basic Knowledge and Conceptional Analysis

3.1 Basic knowledge and its relanvence to this project

Decimal and binary

There are two states in digital logic in binary states: 0 (False) or 1 (True). In analogic voltage, 0 and 1 are corresponding to low voltage (0-0.8V) level and high voltage level (2-5V) respectively. Additionally, one bit has 2 states: 0 or 1 (Kim, 2019).

All numbers in decimal can be converted to numbers in binary, every digit in that binary number represents ‘2 power to n’. Taking 100 as a example:

$$100_{10} = 1 \times 2^6 + +1 \times 2^5 + 0 \times 2^4 + 0 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 0 \times 2^0 = 1100100_2$$

For instance, the first 1 of 1100100 (from left to right), stands for ‘2 power to 6’

Therefore, all integer number can be obtained from addition of these basic number partially: 2^0, 2^1, 2^2, 2^3, 2^4……2^n

Basic knowledge about electronics

The equivilant resistance of resistors in series is given as equation 3.1:

$$R_T = \sum_{i=1}^{n} R_i \quad \text{Equation 3.1}$$

Where: R_T is total resistance in series; R_i is resistance of each resistor

The equivilant capacitance of capacitors in parallel is given as equation 3.2:

$$C_T = \sum_{i=1}^{n} C_i \quad \text{Equation 3.2}$$

Where: C_T is the total capacitance in parallel; C_i is capacitance of each capacitor

From equations and finding above (Dobson et al., 2008), the variable electronic load could be implemented by combining selective resistors in series and capacitors in parallel. The specific selection of resistors and capacitors need to be calculate.

Taking 100Ω as an example, as calculated previously:

$$100_{10} = 1 \times 2^6 + +1 \times 2^5 + 0 \times 2^4 + 0 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 0 \times 2^0 = 01100100_2$$

From left to right:

The 8th number '0' represents 1Ω (False) *The 7th number '0' represents 2Ω (False)*

The 6th number '1' represents 4Ω (True) *The 5th number '0' represents 8Ω (False)*

The 4th number '0' represents 16Ω (False) *The 3th number '1' represents 32Ω (True)*

The 2th number '1' represents 64Ω (True) *The 1th number '0' represents 128Ω (False)*

Therefore, 100Ω=4Ω+32Ω+64Ω, these 3 particular resistors shall be connected in series, while others remain the condition of short circuit.
As for capacitance, connecting particular capacitors can emulate the desired value.

Transistor, is a semiconductor device that controls currents. It has 3 pins: Base (B), Emitter (E) and Collector (C). There are 2 types, PNP and NPN as shown in figure 3.1.2.1. For PNP, current can flow from E to C when B receives low voltage; For NPN, current can flow from C to E when B receives high voltage (Kim, 2019).

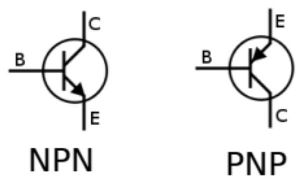

Figure 3.1.2.1: NPN transistor and PNP transistor

For resistors, PNP transistors were used. For capacitors, NPN transistors were used.

3.2 Schematic electrical diagram

Proteus, a British Electronic Design Automation software, was helpful when drawing schematic diagram and simulation. The schematic diagram can be represented as 2 sections: MCU unit and electronic load unit (shown on fig 3.2.1 and fig 3.2.2).

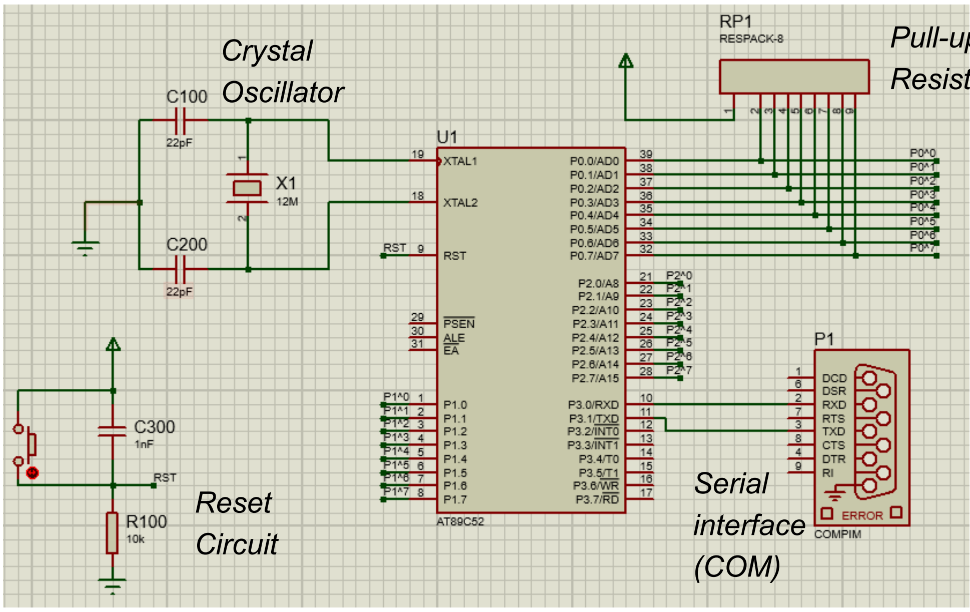

Fig 3.2.1: MCU unit of schematic electrical circuit

As shown in fig 3.2.1, the green nodes stand for electrical connection. There is a node on the right side of Reset Circuit, written RST. There is corresponding another node that is written RST, on the left side of MCU (central object). In this way, the RST port of MCU is connected with Reset Circuit. The representation of electrical connection is also used in the connection of I/O of MCU and Base pin of each transistor in next figure. While simulation on Proteus, it is vital to draw Reset Circuit, Pull-up Resistor, Crystal Oscillator and Serial Interface (COM). Their functions are described below:

1) The circuit can be reset by pressing the button on the Reset Circuit once.
2) I/O of P0 of MCU cannot output real high voltage level. When controlling MCU to output high voltage level, the Pull-up Resistor is to set the voltage at a high level.
3) MCU has a function of timing. Crystal oscillator is an essential component of clock circuit. The clock frequency, XTal, need to be set at 11.0592 MHz.
4) Serial Interface (COM) is significant channel to achieve the purpose of serial telecommunication between PC and MCU. It adopts standard of RS-232.

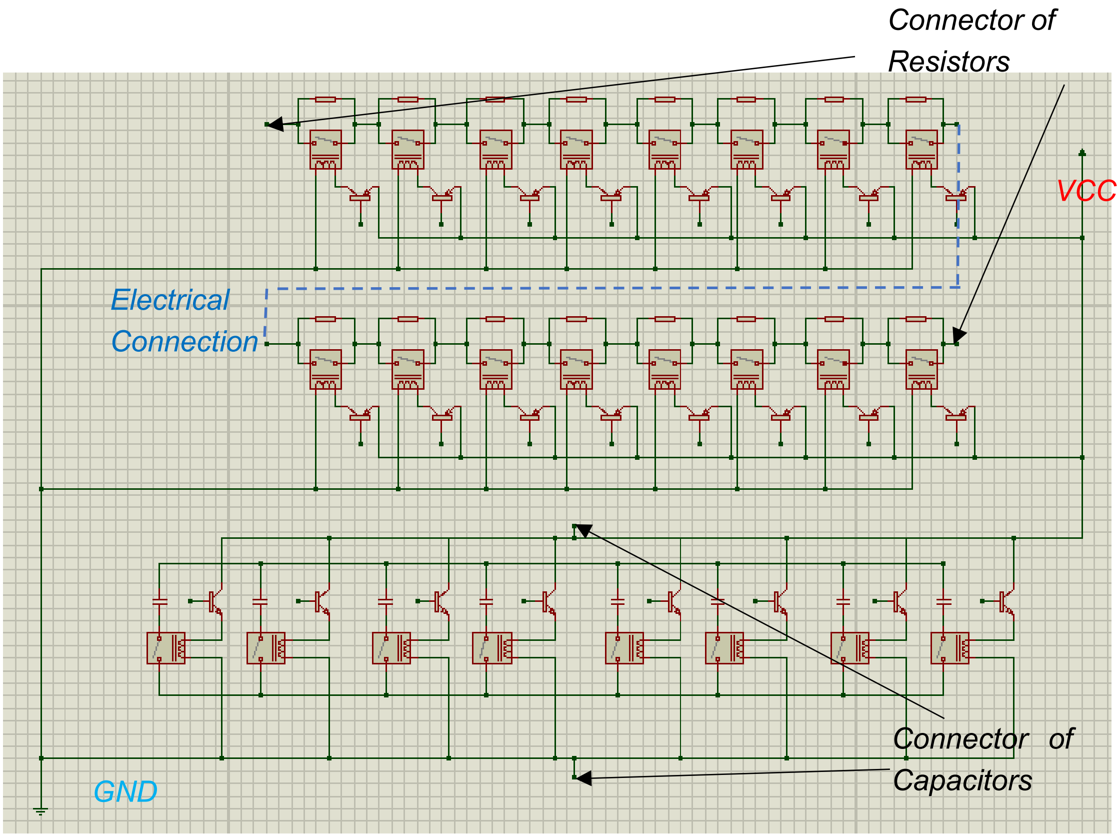

Fig 3.2.2: Electronic load unit of schematic electrical circuit

As shown on fig 3.2.2, every resistor connects with other resistor in series. Every resistor connects with one relay (Normally Open, NO) in parallel.

Every capacitor connects with other capacitor in parallel. Every capacitor connects with one relay (Normally Open, NO) in series.

VCC and GND are abbreviation of Volt Current Condenser and Ground respectively.

The norm of activation of relays as desired, is: MCU outputs a high voltage level when certain resistor or capacitor is desired. By contrast, MCU outputs a low voltage level when it is not desired.

Detailed explanation about how each resistor is connected in the circuit:

Referring to fig 3.2.2, if the resistor is desired to remain in the circuit, MCU outputs a high voltage level from relative I/O, which is connected with the Base pin of PNP transistor. Therefore, current will not flow through Emitter pin (E) to Collector pin (C), and the relay will not be activated. By contrast, if the resistor is not desired to remain, MCU outputs a low voltage level, and current will flow through E to C, causing the activation of relay. In this way, short circuit on the resistor will happen.

Detailed explanation about how each capacitor is connected in the circuit:

If the capacitor is desired to remain in the circuit, MCU outputs a high voltage level from relative I/O, which is connected with the Base pin of NPN transistor. Therefore, current will flow through C to E, and the relay will be activated. By contrast, if the resistor is not desired, MCU outputs a low voltage level, and current will not flow through C to E, causing no activation of relay and open circuit on the capacitor.

3.3 I/O of MCU

16 I/O of P0 and P1 control 16 resistors and 8 I/O of P2 control capacitors. Detailed connection between I/O and electrical component can be found later (chapter 5).

For resistance (≤255) or capacitance:

It varies from 0 to 255. In binary: 0000 0000~1111 1111

There are 8 digits in total. In this case, 8 I/O of P0 and 8 I/O of P2 are in use by resistors and capacitors respectively, while 8 I/O of P1 are not in use.

For resistance (>255):

There are 16 digits in total. It varies from 256 to 65,535. In binary: 0000 0001 0000 0000~1111 1111 1111 1111

In this case, 8 I/O of P0 and 8 I/O of P1 are in use by resistors at same time.

Overall, 16 I/O were used to control resistors. Resistors' resistance varies from 2^0, 2^1, 2^2 …… to 2^{15} Ω. 8 I/O were used to control capacitors. Capacitors' capacitance varies from 2^0, 2^1, 2^2 …… to 2^{15} μF.

Chapter 4: Conversion to Real Application

4.1 Programming and digital control interface

Keil, an American software for C language development systems of MCU, was used. After development, codes could be converted to hex file, which could be stored in the chip of MCU. Real image of STC89C52 (MCU) can be found on fig 4.1.1.

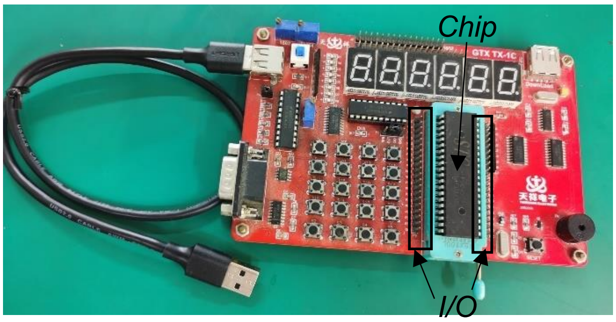

Figure 4.1.1: STC89C52

LabVIEW, an American software to develop graphic programming, was used to create a digital control interface in this project. VISA (Virtual Instruments Software Architecture) is applied. The node used for serial communication in LabVIEW is actually the VISA section points to realise the configuration of serial port, writing of serial port, reading of serial port, close of the serial port (Xu& Fang, 2018). Baud (basic configuration parameter for communication) is set to 9600. Front panel and VI of LabVIEW to achieve the function of digital control can be found on fig 4.1.2&4.1.3.

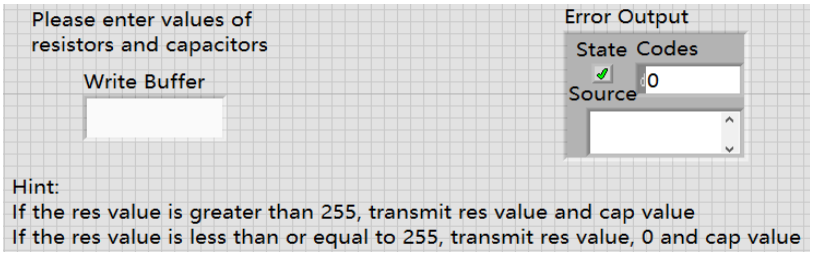

Figure 4.1.2: Front panel (Digital control interface)

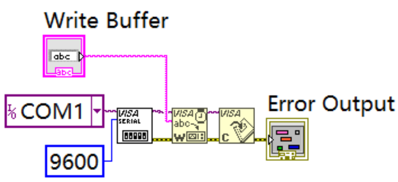

Figure 4.1.3: VI of control interface

4.2 Selection of resistors and capacitors

It is impossible to purchase the resistors and capacitors with regular values. Therefore, to replace original resistors which cannot be bought, combination of 2 resistors in series and 2 capacitors in parallel can substitute original ideal ones. The selection of combination and relative connection to I/Os can be found in table 4.2.1.

Table 4.2.1: Detailed selection of combination of R and C and their relative connection to I/Os

Ideal value for R	Real combination for R	Ideal value for C	Real combination for C
1 (2^0)-P0^0	1	1 (2^0)-P2^0	1
2 (2^1) -P0^1	1+1	2 (2^1) -P2^1	1+1
4 (2^2) -P0^2	3.9+0.1	4 (2^2) -P2^2	3.3+0.47
8 (2^3) -P0^3	4.7+3.3	8 (2^3) -P2^3	4.7+3.3
16 (2^4) -P0^4	15+1	16 (2^4) -P2^4	10+4.7
32 (2^5) -P0^5	12+20	32 (2^5) -P2^5	33
64 (2^6) -P0^6	51+13	64 (2^6) -P2^6	33+33
128 (2^7) -P0^7	120+8.2	128 (2^7) -P2^7	100+33
256 (2^8) -P1^0	220+36		
512 (2^9) -P1^1	430+82		
1024 (2^{10}) -P1^2	1k+24		
2048 (2^{11}) -P1^3	2k+47		
4096 (2^{12}) -P1^4	3.9k+200		
8192 (2^{13}) -P1^5	8.2k		
16384 (2^{14}) -P1^6	16k+390		
32768 (2^{15}) -P1^7	30k+2.7k		

As shown from table 4.2.1, Most combinatorial values are very close to the ideal value, and a few combinatorial values are equal to the ideal value.

4.3 Relay modules

Relay is an automatic control component, widely used in automatic control system, remote control, telemetry system, and communication system. Recently, in defense and aerospace applications, various relay control function devices and corresponding circuits are designed to be integrated into a control box, which has the required current and voltage control functions of the system. It is called relay modules (Zhai, 2009). Otherwise speaking, functions of ordinary relays and transistors have been integrated together. Figure 5.3.1 shows an 8-channels relay module.

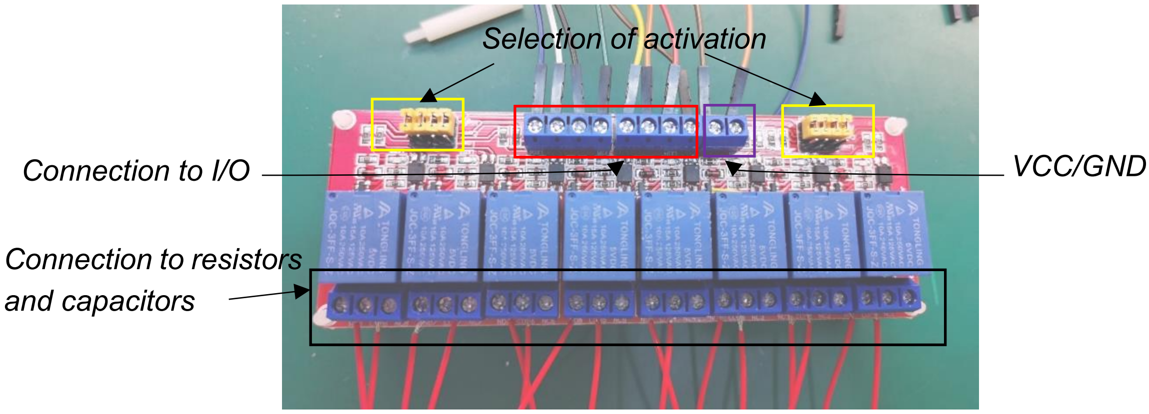

Figure 4.3.1: 8-channel relay module

Users are free to choose activation way of relays by either high or low voltage level. Referring previous chapter, relay was a NO type, connecting COM (Common Port) and NO to electrical components, the previous design could be achieved.

4.4 The first design and optimization

After the completion of conceptional design and preparation of apparatus, the circuits should be connected. Figure 4.4.1 shows the first design of electronic load. In this project, an electric soldering iron was used to solder pins and wires so that electrical components could be connected in a proper way.

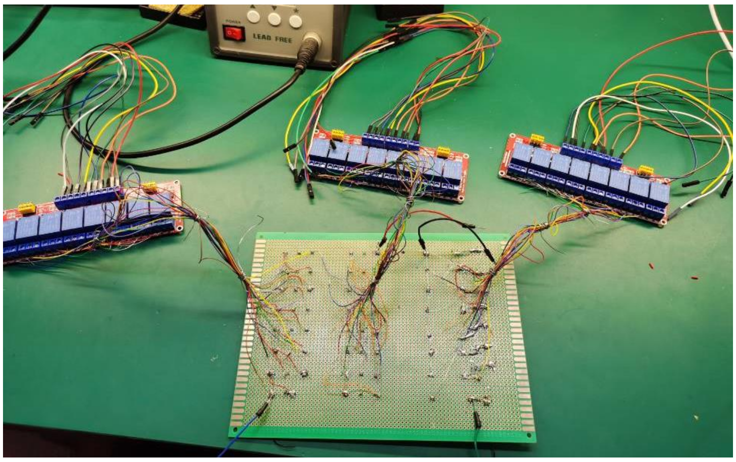

Figure 4.4.1: First design of electronic load

However, serious problem was discovered. As wires were soldered on back side of the universal board, there is gravity force of board exerted on wires when testing. Wires would come off the solder joint. Besides, the exposed part of wires was too long, electrical leakage and short circuit would probability happen. And wires were placed and soldered messily, which might bring difficulty when testing. Redesign and optimization were necessary to conduct.

4.5 The final product

Figure 4.5.1 shows the final product of electronic load. The top 2 2-channel connectors were terminals for external devices such as the multimeters. Other connectors needed to be connected with relays in sequence.

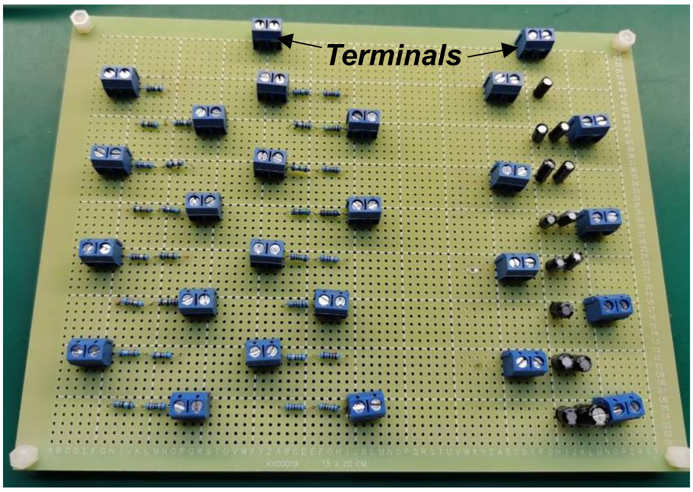

Figure 4.5.1: The final product of electronic load

Figure 4.5.2 shows the overall of all apparatus in condition of use.

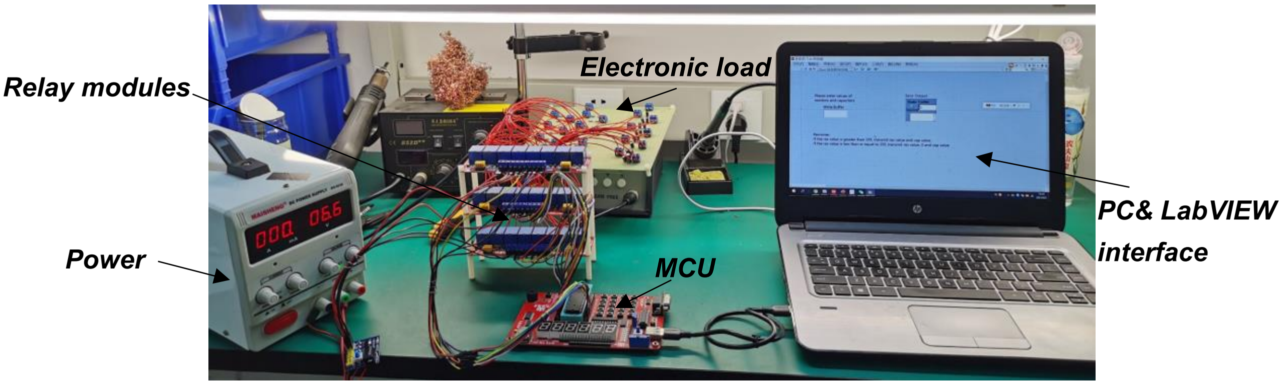

Figure 4.5.2: Overview of all experimental apparatus (in use)

LabVIEW Interface of PC communicated with MCU via COM. To executing a series of operations, codes of C language had been converted to hex file and stored in the chip of MCU. After receiving data from PC, MCU would send relative electrical signal from every I/O, which was connected with relay modules. Power source supplied electricity to drive activation of relay modules as desired.

Empirically speaking, MCU should be grounded externally.

Connecting 2 wires to resistors terminals and using a multimeter, the experimental data could be acquired.

Chapter 5: Experimental Data and Discussion

5.1 Experimental data

To measure data, a general multimeter to measure high resistance and an advanced multimeter to measure low resistance were utilised. The latter one (as shown on fig 5.1.1) could display many digits after decimals, improving precision. However, it had demerits, such as long waiting time for stabilization.

Figure 5.1.1: Advanced multimeter

If entering 100Ω on LabVIEW interface, the partial activation of relay modules is shown on fig 5.1.2. Since 100=4+32+64, relays not parallel with 4, 32, 64Ω were activated to cause short circuit, relays parallel with these 3 resistors were not.

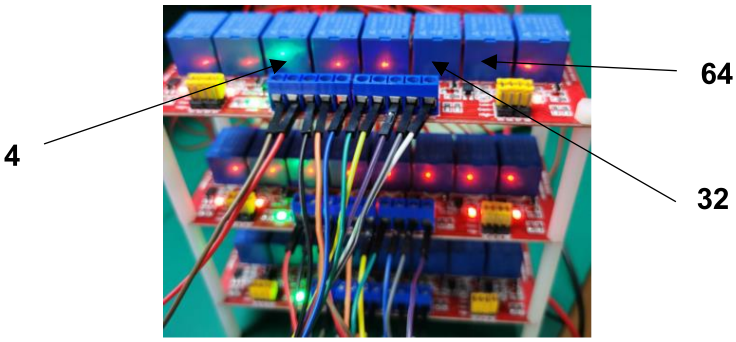

Figure 5.1.2: Partial activation of relay modules (R=100 ohms)

There were not red dots reflected on the relay box for these 3 particular relays.

Table 5.5.1 lists the experimental data and corresponding relative error. 25 set of data in different range had been recorded.

Additionally, there was resistance when all resistors are in short circuit (Bi, 2021).This datum (termed as no-load reisistance) was also needed to be taken.

Table 5.1.1: Experimental and ideal resistance data

Ideal value	Anticipated value	Real value	Relative error
0	0	1.935	---
1	1	2.885	65.34%
2	2	3.873	48.36%
4	4	5.867	31.82%
5	5	6.719	25.58%
8	8	9.833	18.64%
16	16	17.61	9.14%
32	32	33.672	4.97%
50	50	51.266	2.47%
64	64	65.306	2.00%
80	80	81.021	1.26%
128	128.2	129.612	1.24%
256	256	258	0.78%
400	400.2	401.1	0.27%
512	512	509	0.59%
700	700.2	695	0.72%
1024	1024	1023	0.10%
2048	2047	2040	0.39%
4096	4100	4062	0.84%
5000	5004.2	4970	0.60%
8192	8200	8180	0.15%
10000	10008	10080	0.79%
16384	16390	16310	0.45%
20000	20005	20130	0.65%
32768	32700	32770	0.01%
65535	65484.2	65325	0.32%

Explanation:

For ideal value, it was what user wanted and input in LabVIEW interface.

For anticipated value, it was labelled resistance of 2 resistors in series or 1 resistor.

For real value, it was measured by the multimeter.

Relative is frequently used to measure the deviation of real value from ideal value.

Calculation for relative error can be calculated by equation 5.1 below:

$$Relative\ error = \left|\frac{Real\ Value - Ideal\ Value}{Real\ Value}\right| \times 100\% \qquad \text{Equation 5.1}$$

Real value and ideal value’s meaning are described previously.

5.2 Error analysis

Statistics of relative error can be acquired by a pie chart and a table, as shown on chart 5.2.1 and table 5.2.1.

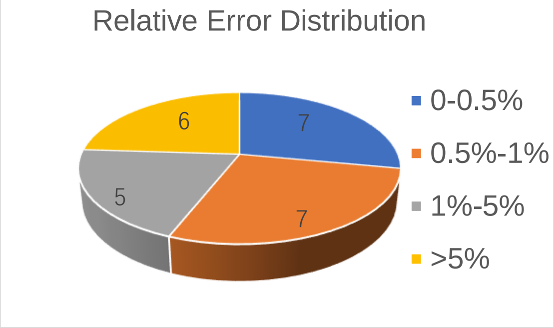

Chart 5.2.1: Statistics of relative error

Error Range	Number
0-0.5%	7
0.5-1%	7
1%-5%	5
>5%	6

Table 5.2.1: Statistics of relative error

According to the table 5.1.1, 5.2.1 chart 5.2.1, it reveals that there were 6 set of data (relative error >5%). Their ideal resistance was all below (or equal to) 16Ω.

Error ranging from 1%-5% was corresponding to resistance varying from 32 to 128Ω.

As for the rest of data, the error was acceptable for medium and high resistance.

To analyse them, there are several reasons causing error. Briefing speaking, these reasons caused high relative error while low resistance.

1) The effect of no-load resistance. The no-load resistance was 1.935Ω while all resistors were in short circuit. It was too great to be ignored when the total resistance was low. However, this effect can be eliminated.
2) Salesman stated that the error allowance of resistors is within 1%. Followed table (table 5.2.2) was what author measured at laboratory about comparison between measured and ideal resistance.

   As shown from the table, there is a host of error while low resistance. By contrast, there is little error while medium or high resistance.

Table 5.2.2 Measured values and ideal values of resistors

Ideal value (Ω)	Measured value (Ω)	Exceed error allowance?
0.1	0.232	YES
1	1.131	YES
20	20.218	YES
200	198.584	NO
2000	1988.61	NO
30000	29901	NO

3) Current flew through either resistors or wires. The resistance of wires cannot be neglected when current flew through most wires while most resistors were in short circuit. The resistance of a wire of 30 AWG (American Wire Gauge) was 0.38Ω when the length was 45mm. The resistance of normal red wire was 0.158Ω with length of 27mm. The resistance of Dupont wire was 0.305Ω with length of 32mm.
4) The resistance of solder cannot be neglected. It is found the resistance of solder with diameter of 0.8mm and length of 1m is 0.295Ω. The resistance with diameter of 0.5mm and length of 1m is 0.802Ω (What is resistance of solder wire, 2020).
5) There is no doubt that the resistance of relays existed. The basic structure of a relay is a switch. Therefore, the resistance was 0.192Ω when activation.
6) Electricity leakage on the universal board happened due to technical mistake. While soldering, partial molten conductive solder may flow together after solidification, causing electricity leakage.
7) The effect of stray capacitance and stray inductance. Pure resistance, capacitance and inductance are idealized concept, which do not exist in reality. Any two conductors will form capacitance, even between two points of the same conductor, but at low frequencies the equivalent impedance of the capacitance, compared with the resistance itself, is little, but at high frequencies, it cannot be ignored. As long as there is a conductor, there is inductance. It is little at low frequencies. But at high frequencies, it cannot (Jiang, 2018).

5.3 Demerits

Every coin has 2 sides. The current design owned some disadvantages.

1. There were too many wires. It not only played a negative role in aesthetic consideration, but also brought negative effect, such as stray capacitance.
2. There was high relative error when resistance was low (reasons stated before).
3. When conducting experiment, all experimental apparatus had to be assembled on the workbench one by one, which costed a host of time.

5.4 Approaches to reduce error

Below lists some approaches to minimize error.

1) When entering a low resistance, subtract 2Ω at first to eliminate the effect of no-load resistance, by which subtracted resistance can be compensated.

2) Invest more fund to purchase high precise instruments. It is best to purchase resistors with low error allowance, relays wires and solder with least resistance.

3) Be careful and concentrate when soldering. Try to avoid molten solder to collect together. If happening, the best way is to melt it, use solder sucker and resolder.

4) To restrain the effect of stray inductance and capacitance, use less &short wires.

5) In existing situation, connect a new electronic load in series and another new one in parallel with existing electronic load, and the new design is illustrated on fig 5.4.1. The function of new electronic load in series (#2) is to increase the total resistance (when real resistance<ideal resistance). The function of new electronic load in parallel (#3) is to decrease the total resistance (when real resistance>ideal resistance).

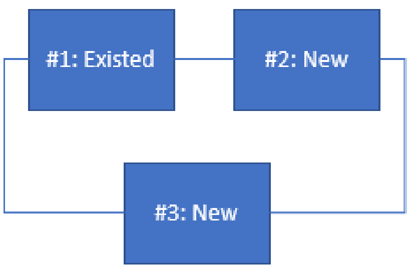

Figure 5.4.1: New design of electronic load

For example, if ideal resistance (entered in LabVIEW interface) is 100Ω.

When the real resistance is 99Ω, set #2 to output 1Ω since 99+1=100

When the real resistance is 110Ω, set #3 to output 1100Ω since $\frac{1}{100} = \frac{1}{110} + \frac{1}{1100}$

By Replenishing codes of C language in the chip in advance, the smart output and control can be achieved, despite requirement of more MCU, wires, solder, relays, and reintroduction of error.

5.5 Comparison to industrial product

NH Research, locates at California of the U.S., is famous for power conversion and power supply test systems. Its products are widely utilised in industries, engineering. Taking 4700 Series High-Current DC Electronic Load product of NH Research as an example, accuracy data could be tabulated on table 5.5.1.

Table 5.5.1: Accuracy data of 4700 Series DC Electronic Load of NH Research (2021)

Programmable Modes		Measurements	
Application	Accuracy	Application	Accuracy
Constant Current	0.12%+0.08%	Current	0.12%+0.06%
Constant Voltage	0.05%+0.05%	DC Voltage	0.01%+0.02%
Constant Power	1%+1%	Power	0.13%+0.08%
Above Accuracies: % of Set + % of Range			
Constant Resistance	2%		

Developed variable load emulator (based on DC electronic load) cannot be used for small resistance due to unacceptable error (>5%). From the table 5.1.1 and 5.5.1 above, for resistance (>50Ω), the relative error tended to drop from 2%, which is similar with accuracy of Constant Resistance modes of 4700 Series. Assuming the function of developed emulator could be more complex by upgrading, for resistance (> 128Ω), the performance of developed emulator cannot exceed the performance of 4700 Series, since the emulator's error fluctuates (0.01%-0.84%) and cannot stabilize to a very small value. By contrast, the accuracy of 4700 Series can be stable at a very small value.

Overall, accuracy of developed emulator is moderate (less than 1% when resistance >128Ω), but there is large difference, compared with industrial product, 4700 Series DC Electronic Load of NH Research.

5.6 Improvement of precision

The developed electronic load is capable to emulate the resistance in integer number. But it is hard to emulate resistance in non-integer number. Current precision is a fault. It can be optimized by extra combination of resistors in no-integer values. The precision can be upgraded to '1 decimal place' level by using 4 resistors (0.1, 0.2, 0.3, 0.4 Ω), since 0.1-0.9Ω can be implemented by connecting partial resistors among these 4 resistors, due to the theory of binary. However, referring to previous content on '5.2 Error analysis', this idea can be eliminated because of previous sources of error. Therefore, a sophisticated system with the function of measurement and feedback regulation should be considered.

Illustrated flow chart with an example can be found on fig 5.6.1. If user wants resistance in a non-integer number, based on binary systems, adjacent resistance's number shall be emulated in turns and their real resistance shall be measured in turns. If the gap is not close, using feedback to return to initial position and reselect several resistances to be emulated. The resistance with lowest difference shall be selected. Final difference can be compensated with low resistance to be connected.

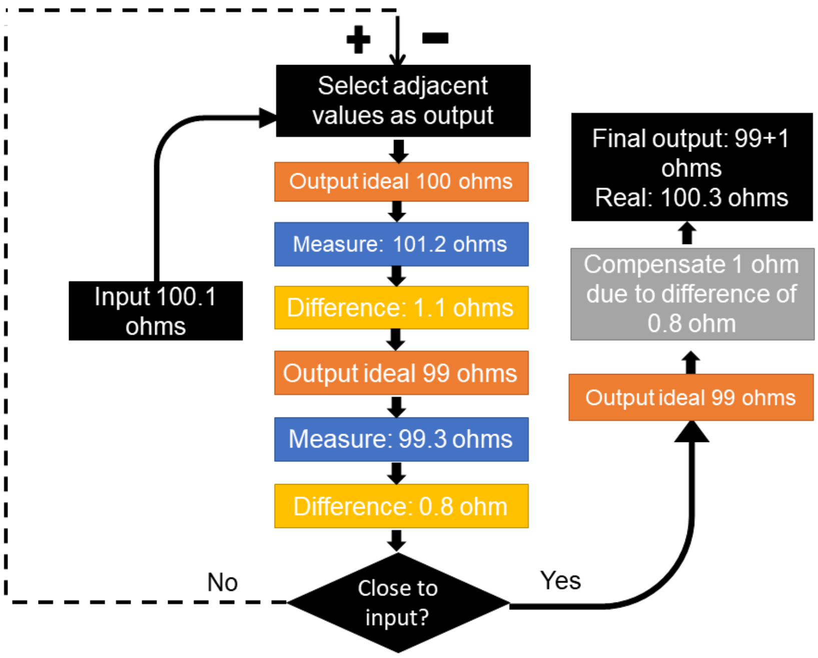

Figure 5.6.1: Example of sophisticated systems for precision improvement

As shown from the example, ideal value (100.3Ω) is very close to real value (100.1). But it involves complex C language, which makes it harder to implement.

Chapter 6: Conclusion

6.1 Achievements

In this project, *a Variable load emulator with a digital control interface* is implemented at laboratory. It owns many merits, such as:

1) Large output range: The resistance output varied from 0-65,535 Ω. The capacitance output varied from 0-255 μF.
2) High precision: The output was continuous. The calibration of output was 1.
3) Low resistance error (when medium or high resistance): As previous error distribution, most relative error was small when the resistance was medium or high. It became highly precise when outputting a high resistance.
4) Safety: The heating of electrical components was not severe. Power supply for relay modules was only around 5V. Users will not hurt themselves.
5) Easy to control and maintain: LabVIEW interface can be used to input desired values. As long as connecting it to PC, it can work successfully (with external power source to activate relays).

6.2 Discussions

Normally, MCU owns a function of grounding when connecting COM to PC. At beginning, MCU did not work properly. It was empirically found that MCU need to be grounded at one of its GND of I/O externally.

Compared with other researchers' work about electronic load, this particular one owns many advantages, such as no requirement of feedback, easy to control. Demerits, such as high relative error when low resistance, have also been discussed.

Referring to previous chapter, the relative error was less than 5% when resistance was greater than 16Ω. Developed electronic load can meet the requirement of high or medium resistance value successfully. However, the design cannot be utilised to emulate a low resistance directly. Reasons (such as the effect of no-load resistance) and solutions (such as subtracting 2Ω before inputting) are all proposed.

A suitable approach to reduce error at most is to connect 2 new electronic loads to tune resistance (Detail can be found in 5.4 Approaches to reduce error).

Comparison to industrial product, DC Electronic Load of Series 4700 of NH Research, and a sophisticated system with function of measurement feedback regulation to improve precision have been addressed.

6.3 Conclusions

Under rapid development of electronic technology, it is meaningful to study and develop a programmable controlled variable electronic load to emulate various loads to test power source. A variable load emulator with a digital control interface was implemented by combining a host of electrical components, including MCU, resistors, capacitors, relay modules and so forth. Storing codes of C language into the chip of MCU promoted the function of 'programmable control' with existence of LabVIEW interface. Finally, a high precise electronic load is developed, with a host of advantages, such as no requirement of feedback, high safety, low relative error. It is capable to emulate the electronic load and be ready to conduct static or dynamic experiments. Approaches to minimize error, comparisons and optimizations are also proposed. The aim and objectives are completed step by step.

6.4 Future work

To emulate electronic load, connecting the product with static or dynamic power can make the research deeper, and the characteristics of power can be determined and evaluated. Example of testing power sources is shown in fig 6.4.1.

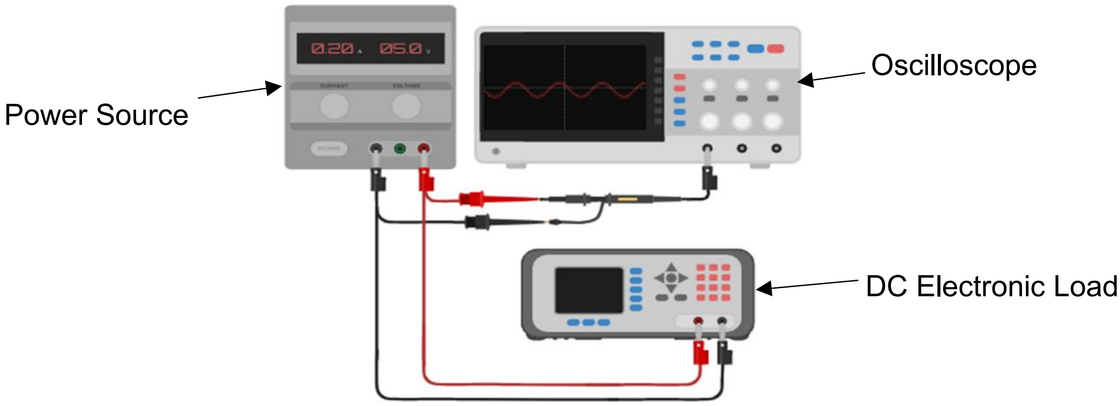

Figure 6.4.1: Schematic diagram for testing of power source (Carlson, 2016)

It is necessary to minimize error, such as using 2 new electronic loads, investing more, and subtracting 2Ω as emphasized previously.

Referring to literatures, researchers prefer to use MOSFET and STM32 when designing electronic loads. Research on these topics can bring deeper knowledges and skills in addition to merits such as greater power, real-time control, and so forth. Currently, all apparatus had to be assembled on the workbench one by one when conducting experiments. To provide a box to be placed, a resistor box is urgent to be designed. An illustration is on figure 6.4.2, there will be a digital screen installed on top to indicate the current resistance of capacitance for users. All components, including MCU, resistors, capacitors, relay modules will be placed into the box. COM will be necessary to communicate between MCU and PC. 2 wires connecting VCC and GND shall be set. This kind of design can make current electronic load advanced and sophisticated. Nevertheless, the technique of PCB (Printed Circuit Board) and proper usage of Altium Designer software may involve.

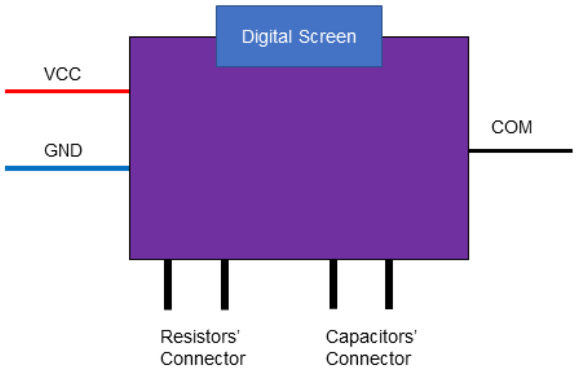

Figure 6.4.2: New design of resistor box

Chapter 7：Reference

1. Akhlaghi, S. Zolghadri, M. 2020. Predictive Current Control for Programmable Electronic AC Load. *IEEE.*
2. Al Ameri, O. Serban, M. Lamont, L. El Chaar, L. 2009. Variable Electronic Load for Testing PV Performance. *Direct Conversion of Solar Energy to Electric Energy*. **46** (2), pp.89
3. Anon. 2017. *Analysis of the difference and advantages and disadvantages between AVR microcontroller and STM32*. [Online]. [Accessed 8 April 2021]. Available from: http://m.elecfans.com/article/599548.html
4. Anon. 2018. The invention relates to a programmed electronic load device capable of generating voltage output and a test method thereof. 201810577309.5
5. Anon. 2020. *Several common microcontrollers*. [Online]. [Accessed 8 April 2021]. Available from: http://m.elecfans.com/article/1205230.html
6. Arduino. 2021. *Arduino Edge Control*. [Online]. [Accessed 8 April 2021]. Available from: https://store.arduino.cc/usa/edge-control
7. Arduino. 2021. *Arduino-Home*. [Online]. [Accessed 9 May 2021]. Available from: https://www.arduino.cc/
8. Bi, Y. 2021. Conversation with Zixiang Zhao, 8 April.
9. Carlson, C. 2016. *Power Supply Testing*. [Online]. [Accessed 5 May 2021]. Available from: https://www.maxbotix.com/Tutorials/127.htm
10. Ding, R. 2008. *Research on new electronic load*. Master thesis, North China University of Technology
11. Dobson, K. Grace, D. Lovett, D. 2008. *Physics*. 3rd edition. London: Collins.
12. Feng, B. Su, J. Liu, W, Peng, C. 2011. Photovoltaic array characteristic test technology based on variable electronic load. *Power Electronics*. **45**(9), pp.38-45
13. Fu, G. 2017. Study on the design of programmable DC electronic load for STM32. *Electronic Commerce.* pp.143-144
14. Geng, Z. Gu, D. Hong, T. Czarkowski, D. 2018. Programmable Electronic AC Load Based on a Hybrid Multilevel Voltage Source Inverter. *IEEE Transactions on Industry Application*, **54** (5), pp.5512
15. Infineon. 2021. *Power MOSFET*. [Online]. [Accessed 25 April 2021]. Available from: https://www.infineon.com/cms/cn/product/power/mosfet/
16. ITECH. 2018. *IT8500+ Series programmable DC electronic loads*. [Online]. [Accessed 9 May 2021]. Available from: https://cdn.itechate.com/cn/product/info_43.aspx?itemid=46&lcid=6
17. Jiang, Y. 2018. What is stray capacitance? 7 May. *What is stray capacitance?* [Online]. [Accessed 13 April 2021]. Available from:

https://www.zhihu.com/question/276281845
18. Kim, J. 2019. *Mechatronics*. Lecture notes distributed in XJME2650 Mechatronics and Measurement Systems. 9 April, University of Leeds.
19. Liang, Z. 2020. Design and research of active gate feedforward drive circuit for IGBT. *Automation Application*. **04,** pp.1
20. Lin, C. Chen, K. Pai, K. Chen, K. 2020. A Low-Cost Programmable High Frequency AC Electronic Load with Energy Recycling for Battery Module Diagnostics. *Applied Science*. pp.2
21. Liu, J. 2018. Programmable DC electronic load based on STM32. *Electronic Technology*. pp.107-109
22. Liu, H. 2018. *The Research and Development of Program-controlled electronic load*. Master thesis, Nanchang University.
23. Liu, H. Hao, W. 2018. Realization of LabVIEW Program-controlled electronic Load and design of virtual panel. *Design and Development*. pp.13
24. Liu, Z. 2004. *Power Electronics*. Beijing: Tsinghua University Press.
25. Lu, S. Wei, Z. Deng, Y. 2017. The utility model relates to a programmed electronic load used to simulate the teaching of electronic technology. 201610985973.4
26. Mo, X. Zhou, W. Dou, X. Huang, D. Cao, X. Sun, M. Zhao, B. 2015. Design of programmable DC electronic load based on STM32. Electrical Measurement and Instrumentation. **51**(18), pp.85-90
27. Natural Prince. 2020. *What is resistance of solder wire?* [Online]. [Accessed 13 April 2021]. Available from: https://www.bilibili.com/video/av797501722/
28. Nel, G. Doorsamy, W. 2018. Development of an Intelligent Electronic Load Controller for Stand-Alone Micro-Hydropower Systems. *IEEE PES/IAS Power Africa.* pp.366
29. NH Research. 2021. *Document Download Library*. [Online]. [Accessed 8 May 2021]. Available from: https://nhresearch.com/power-electronics-test-systems-instruments-support/document-download-library/#1611772201240-b0cc0c87-a47d
30. NH Research. 2021. *Programmable AC & DC Electronic Loads*. [Online]. [Accessed 25 April 2021]. Available from: https://nhresearch.com/power-electronics-test-systems-and-instruments/ac-dc-electronic-loads/
31. Pan, S. 2005. *Study on High Power AC Electronic Load*. Master thesis, Southeast University
32. Roodsari, B.N. Nowicki, E.P. 2018. Analysis and Experimental Investigation of the Improved Distributed Electronic Load Controller. *IEEE Transactions and Energy Conversion*. **33**(3), pp.905-914.
33. Roslaniec, L. Jurkov, A.S. Al Bastami, A. Perreault, D.J. 2015. Design of Single-Switch Inverters for Variable Resistance/Load Modulation Operation. *IEEE Transactions on Power Electronics.* **30**(6), pp.3200-3214.
34. Singh, B. Murthy, S.S. Gupta, S. 2005. Transient Analysis of Self-Excited Induction Generator With Electronic Load Controller (ELC) Supplying Static and Dynamic Loads. *IEEE Transactions on Industry Applications*. **41**(5), pp.1194-1204.

35. Soaring. 2021. *Energy-saving feedback electronic load solution*. [Online]. [Accessed 9 May 2021]. Available from: http://www.soaring.com.cn/?page_id=620
36. Sunpower Electronics. 2019. *What are Electronic Load?* [Online]. [Accessed 8 November 2020]. Available from: https://www.sunpower-uk.com/glossary/what-are-electronic-load/
37. Xu, Q. 2013. Research and design of programme-controlled DC electronic load. *Technological Development of Enterprise*. **32**(17), pp.3-4.
38. Xu, Q. Fnag, Q. 2018. Application of Serial Communication between LABVIEW and Single Chip Microcomputer in Semiconductor Module Test Equipment. *Value Engineering*. **30**(2), pp.184-185.
39. Xu, X. 2012. *Study on energy - fed electronic Load for power supply detection in ship power station*. Master thesis, Wuhan University of Technology.
40. Wang, Z. 2019. V*ibration measuring instrument design based on single-chip microcomputer*. Master thesis, University of Electronic Science and Technology of China
41. Yan, G. Chen, Z. Zhuang, L. Zhang, M. 2018. Design of multi-channel PV module test system. *Solar Energy.* pp.30-35
42. Yang, Q. He, M. Xu, J. Li, X. Zhu, J. Zhang, Z. Gu, Z. Ren, X. Chen, Q. 2020. Wide Input Voltage DC Electronic Load Architecture With SiC MOSFETs for High Efficiency Energy Recycling. *IEEE Transactions on Power Electronics.* **35**(12), pp.13053-13067.
43. Yang, S. Zhang, D. 2010. The research and design of digital control direct current source based on NIOS. *Electrical Measurement& Instrumentation*. **47**(2), pp.64-67
44. Zhai, C. 2009. *Research on the networked EMC test system for relays and their modules.* Master thesis, Harbin Institute of Technology
45. Zhang, K. Zhu, J. Zhang, M. Wu, M. Shi, Z. 2013. A programmable electronic load for relay protection. 201310236601.8

Appendix (meeting log)

XJME3890 Individual Engineering Project Supervisor Meeting Log

Date of Meeting	Summary of Discussion	Objectives for next meeting	Supervisors Initials
26 Oct	Introduction to the project	Read relative literatures	Weiqun Liu
9 Nov	Be clear about aims, basic theory, background and objectives. Introduction to scoping documents	Finish the scoping documents. Get started with the electrical circuit simulation	Weiqun Liu
23 Nov	Modification and submission of scoping documents, redesign the electrical circuit	Confirm final simulation diagram (Proteus software)	Weiqun Liu
7 Dec	Preparation for ethical essay	Read books about controlling methods, such as MCU (Microcontroller Unit)	Weiqun Liu
28 Dec	Be clear about controlling framework, modification and submission of ethical essay	Read books about programming and application of MCU	Weiqun Liu
11 Jan	Revision on LabVIEW software	Continue to read books (MCU and programming)	Weiqun Liu
25 Jan	Completion of LabVIEW front panel and VI to achieve the purpose of communication	In Chinese New Year festival, finish the part of Proteus design, simulation, after returning campus, prepare to build the circuit	Weiqun Liu

2 March	Start to build the circuit at lab including purchasing, soldering, assembling, etc.	When finish, wait for inspection by postgraduates students	Weiqun Liu
30 March	Completion of real electrical circuit at lab	Measure and test, modify when necessary	Weiqun Liu
13 Apr	Start to write formal thesis, and prepare final presentation	Ask supervisor to examine when completion	Weiqun Liu
4 May	Completion of Power Point of presentation	After 6 May (date of presentation), finish thesis as soon as possible	Weiqun Liu
13 May	Examine final thesis	Submit thesis at next day (14 May)	Weiqun Liu