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Intelligent Battery Tester

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Report submitted in partial fulfilment of the requirements of the module Project (E) 448 for the degree Baccalaureus in Engineering in the Department of Electrical and Electronic Engineering at Stellenbosch University.

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Abstract

English

The 12V/7Ah sealed lead-acid battery is very widely used, commonly in uninterruptible power supplies. A common problem, however, is how to determine when these batteries are reaching the end of their lifetime. The objective for this project was to design and build an Intelligent Battery Tester, specifically the 12V/7Ah type. This was achieved by first looking at existing products and related literature on battery testing methodologies.

Existing methodologies were then combined with empirical experimentation, to develop a rapid test for the Intelligent Battery Tester. This test is able to quickly estimate the health of most batteries. A longer capacity test was also implemented and can accurately measure the capacity of any 12V/7Ah battery. The viability of the rapid test was confirmed by performing both tests on a small sample of batteries and comparing the results.

Afrikaans

Die 12V/7Ah geseëlde loodsuur battery word algemeen gebruik in ononderbroke kragbronne. Die probleem is dat dit moeilik is om vas te stel wanneer hierdie batterye die einde van hul leeftyd bereik het. Die doel van hierdie projek is om 'n Intelligente Batterytoetser te ontwikkel. Dit is gedoen deur te kyk na bestaande produkte en verwante literatuur oor die toets van batterye.

Bestaande toetsmetodes is gekombineer met empiriese eksperimentasie om 'n vinnige toets vir die Intelligente Batterytoetser te ontwikkel. Hierdie toets kan in 'n kort rukkie die gesondheid van die meeste battery skat. 'n Langer kapasiteitstoets is ook geïmplimenteer, wat die kapasiteit van 'n 12V/7Ah battery akkuraat kan meet. Die lewensvatbaarheid van die vinnige toets is bevestig deur beide toetse op 'n klein aantal batterye uit te voer en die resultate te vergelyk.

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Nomenclature

Acronyms and abbreviations

AE	Afrikaans English
IBT	Intelligent Battery Tester
ADC	Analogue to Digital Converter
UPS	Uninterruptible Power Supply
AC	Alternating Current
DC	Direct Current
CA	Cranking Amps
CCA	Cold Cranking Amps
IV	Current-Voltage
I/O	Input and Output
PCB	Printed Circuit Board
GUI	Graphical User Interface
LCD	Liquid Crystal Display
OEM	Original Equipment Manufacturer
VRLA	Valve Regulated Lead Acid
AWG	American Wire Gauge

Chapter 1

Introduction

1.1. Problem statement

The 12V/7Ah sealed lead acid battery is very widely used in a variety of electric devices. Some of these include: uninterruptible power supplies (UPS), alarm or CCTV systems, aircraft signalling and other electronic equipment and apparatus [3]. A common problem, however, is how to determine when these batteries are reaching the end of their useful lifetime.

Most battery testers available online are for consumer electronic batteries like AA's or for car starter batteries. A generic 12V load tester for starter batteries [4] that is available relatively cheaply is not suitable for testing the small 12V/7Ah units as the load current drawn by the tester is very close to the theoretical maximum recommended by the battery manufacturer [3] and these testers are also designed to measure crank amps (CA), an unimportant metric in terms of the applications where 12V/7Ah units are used. Other variations of these cheap testers can measure battery internal resistance, but without prior knowledge of how this relates to battery health it is quite meaningless.

Expensive battery analysers are also available, but usually cost over R20 000, putting them out of reach for most consumers and small businesses. These analysers claim to be very accurate, have the ability to perform rapid health tests and can directly measure capacity by "coulomb counting".

1.2. Project objectives

The aim of this project is to gather some background on testing methodologies, specifically for the 12V/7Ah sealed lead acid battery to determine the health or capacity of said battery. Furthermore, a simple, affordable and easy to use Intelligent Battery Tester (IBT) is to be designed, built and tested. The IBT should be able to estimate the health and capacity of a battery and give the user graphical feedback on both. The system design objectives can be summarised as follows:

- A microcontroller-based board, that can accomplish voltage and current sampling as well as control a variable loading circuit. This includes a resistive divider to measure the terminal voltage and a current sensor module to measure load currents.

- Robust loading circuit capable of binary-style load variations that can be sustained for longer periods to allow complete discharging of batteries. The circuit should be able to dissipate a maximum of 180W or 15A from the battery and be controlled from a low current source such as a microcontroller.
- An I/O PCB for housing signal conditioning components, distributing power to the system and allowing signalling between the control and loading circuits.
- GUI that is easy to use, gives graphical feedback and has a touch interface to allow an intuitive operation of the IBT.
- All sections of the intended IBT system should be, as far as possible, off-the-shelf to allow drop-in replacements with minimal recalibration. This would also allow the system to be more easily repaired or upgraded in future.
- A test protocol that allows rapid testing of batteries at the ”definitely good” and ”definitely bad” ends of the spectrum. A capacity test will be used as a last resort, as such a test takes much longer to run, but will ensure the IBT can accurately measure the capacity of all 12V/7Ah lead acid batteries.

1.3. Project scope

The scope for this project was intentionally limited to ensure a good solution to a specific problem. The following will not be covered in this project:

- The only batteries this project will be concerned with, are the 12V/7Ah lead acid types, commonly used in UPS's. The IBT will still work on higher capacity UPS-compatible lead acid batteries, but may give overly optimistic results. All other batteries are excluded from the project scope.
- The intended system is designed to only measure fully charged batteries, because the intended use case of the IBT is for testing batteries from UPS's, alarm systems and gate motors. This means that most batteries being tested will be fully charged at the time of testing and will be recharged when placed back in the device, pending possible replacement. Measurement of discharged batteries will not be covered in this project.
- The testing protocol to be implemented in the IBT will not include AC conductance measurements due to the limited switching rate of the relay modules. More expensive solid-state switching components would be required to conduct such a test, which

defeats the intention of designing a more economical, but advanced battery testing system.

1.4. Contents of report

Chapter 1: This chapter includes the project problem statement, objectives, scope as well as a summary of the project.

Chapter 2: Chapter 2 deals with work related to this project, such as other existing solutions and test methodologies.

Chapter 3: This section covers the design philosophy, proposed concept and gives a high level overview of hardware and software technology choices for the IBT system.

Chapter 4: The chapter details individual component choices for the hardware design, a hardware test and test methodology design for the IBT system.

Chapter 5: Chapter 5 presents test viability results and covers overall system performance of the IBT.

Chapter 6: The final chapter gives a summary of the project as well as a conclusion on the successfulness of the endeavour.

Chapter 2

Background and related work

2.1. The 12V/7Ah battery

Lead acid batteries were one of the first rechargeable batteries developed and were the first to be used commercially. Today these batteries are very widely used thanks to their low cost and high reliability. A lead acid battery consists of a positive lead dioxide electrode and a negative lead electrode submerged in a concentrated sulphuric acid solution. Through a process of reduction and oxidation, the battery can be charged or discharged [1].

A typical 12V/7Ah lead acid battery is shown in Figure 2.1. This variant is better known as a valve regulated lead acid (VRLA) battery and is widely used for UPS applications thanks to effectively being spill-proof [1].

Figure 2.1: A typical 12V/7Ah battery.

An important concept to take note of when dealing with batteries are discharge rates, given in C-rate. Most small lead acid batteries are used at 1C. A 1C rate means that a 7Ah battery is discharged at 7A and is able to maintain this current for 1 hour before being completely discharged [1].

All lead acid batteries suffer from surface charge effects after being removed from a charger. This effect is caused by the slow conversion of lead sulfate to lead on electrode surfaces when charging and will give elevated state-of-charge readings. This effect can also lead to elevated internal resistance measurements. Battery University recommends discharging 2% of the nominal battery capacity before testing internal resistance to minimise surface charge effects [14].

As lead acid batteries age, the electrodes slowly corrode which causes shedding of lead particles from the electrodes. These particles then stop contributing to the capacity of the battery reducing the effective capacity and increasing internal resistance over time.

2.2. Existing solutions

It is often difficult to decide when a UPS battery has aged to an extent where it needs to be replaced. The most common type of UPS battery being the generic 12V/7Ah unit. There are a wide range of battery testers and analysers available, with varying functionality. The majority of these claim quick and accurate results but give little to no information on how the test is actually conducted.

2.2.1. Rapid test devices

Most battery testers or analysers are one of two types: The first consists of devices aimed at testing the cranking amp (CA) capability of automotive batteries. These testers are inexpensive, ranging from R500-R2000. Some of these testers place the battery under a simulated cranking load, usually in the order of 100-200A, and then measure the drop in terminal voltage to determine battery health. The OCT 3180 is a good example of such a tester [5]. Testers like this would place the battery right at the 100A limit suggested by the battery manufacturer [3] and are thus not really suitable for this our application because UPS's do not draw that much current. Other testers that are similarly inexpensive usually have some digital control/logic that places batteries under light loads to measure the internal resistance. All further analysis conducted by these testers simply relates the internal resistance to the crank amps (CA) rating, which is combined with some information from the user like battery type and capacity to determine if the battery is still capable of starting a vehicle. The Foxwell BT100 and its derivatives are quite popular in this segment. Regrettably, all these devices give little to no detail on how the test is conducted or how much capacity remains available [4]. This latter information is important when regarding the typical type of load 12V/7Ah batteries are subjected to.

The other type of battery tester consists of much more advanced devices that can vary load current and even apply AC loads to calculate battery capacitance and inductance. These devices are much more expensive however, costing in excess of R20 000, excluding software licensing. Cadex and Fluke Corporation are the main manufacturers of this type of battery analyser. Details on what analysers like the Cadex C7400 measure is readily available in the product brochure. The information provided in the brochure [6] revealed that the analyser itself takes similar measurements, albeit at more realistic load currents, to for example the BT100. The difference, however, is that Cadex includes a database of test configurations for most small batteries, including 12V/7Ah lead acid types. This allows the analyser to predict battery health quickly, based on large sets of well researched data. Analysers in this category also normally give the user a printout or report on the test result, with the option to log results.

2.2.2. Other tests

It is possible to measure internal resistance by manually subjecting a battery to varying loads and taking measurements. This requires experience, can be time consuming and also demands prior knowledge on how internal resistance relates to capacity in the case of 12V/7Ah batteries. This is impractical and out of reach for most users, due to a lack of published research data and the technical experience required. This apparent lack of published research data was attributed to the monetary incentive of keeping the information proprietary.

Battery capacity can also be measured directly through discharging and measuring energy transfer. This would always give clear and accurate results, but has the same limitation as mentioned previously, namely that the technical skills and time required make it impractical for regular testing.

2.3. Test methodologies

Various test methodologies exist for measuring battery performance and capacity. Rapid test accuracy is limited, however, due to the ”black box” nature of electrochemical cells.

2.3.1. Internal resistance and load I-V characteristics

Today, the most common test performed on lead-acid batteries is the two-tier DC load test as outlined by the IEC 61951-1:2005 standard [1]. Internal resistance can be determined using this method and is useful for estimating CA capability of batteries without needing to place the battery under heavy load. A research paper by Glenn Albér points out that internal resistance can also be used to make reasonable predictions of battery capacity, but that the relationship is non-linear [7]. Internal resistance is thus not to be used as a direct predictor of battery capacity, but rather as a warning indicator for overall health. The paper suggests using internal resistance as a cost-effective alternative to load testing and includes a rule-of-thumb that batteries with an internal resistance that is 25% above the nominal value will most likely fail a capacity test (less than 80% remaining capacity).

Figure 2.2 shows the loading pattern recommended by the IEC. The DC internal resistance can be calculated according to the following equation:

$$R_{DC} = \frac{V_1 - V_2}{I_2 - I_1} \tag{2.1}$$

where V_1 and I_1 are the terminal voltage and current when the battery is under the light load and V_2 and I_2 are the measured values under a heavier load. The light load is sustained for at least 10 seconds, while the heavy load for at least 3 seconds. Current and voltage are sampled at the end of each period. These values are then used in Equation 2.1 to determine the DC internal resistance of the battery.

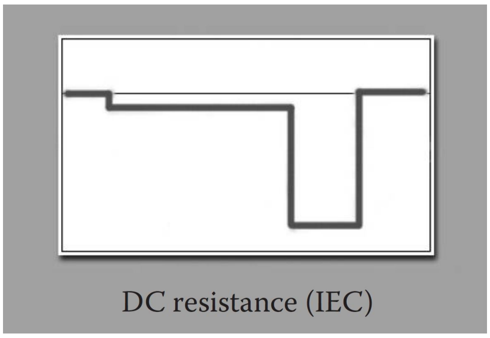

Figure 2.2: Two-tier DC load waveform [1].

The performance of a battery under realistic load conditions is arguably the best way to gauge battery health. Plotting the terminal voltage against the load current of the battery under various loads could give more insight into the health of the battery by graphically representing performance under load. A single internal resistance value may not always tell the full story as it only considers two distinct load levels. An IV-curve across a wider range of load conditions may give a much better indication of battery health. Figure 2.3 gives an example of such a curve.

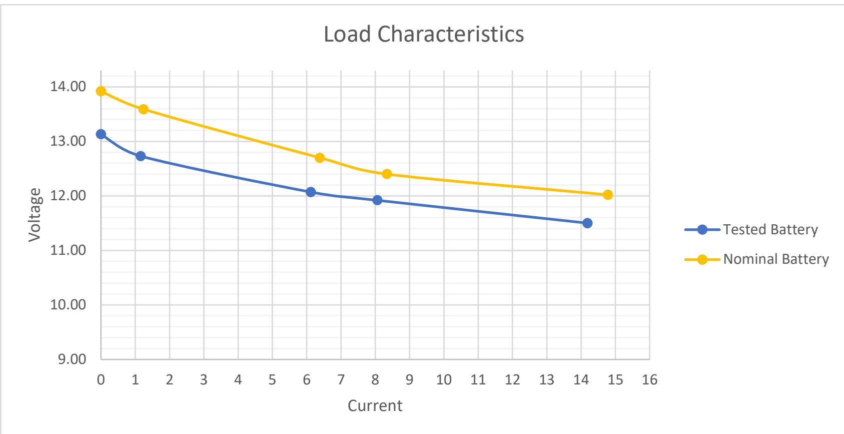

Figure 2.3: Example I-V curve.

2.3.2. Coulomb counting

Coulomb counting involves integrating the current flowing from a source such as a battery over time. When only integrating current, the measurement gives an Ah rating. It is also possible to integrate the power delivered by the source to obtain a measurement of Wh.

The latter is more useful when applying a resistive load, because the terminal voltage drops as the battery is discharging.

$$\int_a^b f(x)dx \approx \sum_{n=0}^{N-1} f_n \cdot (x_{n+1} - x_n) \tag{2.2}$$

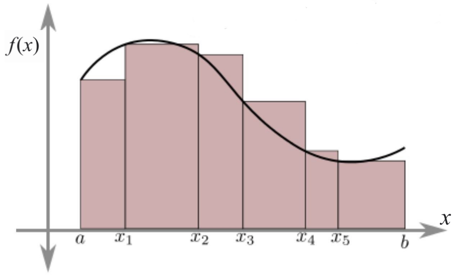

Figure 2.4: Riemann approximation of an integral from a to b [2].

To integrate power in real-time, it must be done by discrete approximation when using a digital device such as a microcontroller. The simplest way to implement this is by sampling power at regular intervals and using a Riemann sum to approximate the integration. See Equation 2.2 and Figure 2.4 for an example of the implementation. This method will introduce some error in the measurement, but because the battery voltage drops slowly when discharging this error should be negligible if the sampling rate is sufficiently high.

2.4. Chapter summary

This chapter covers some background information about 12V/7Ah batteries, existing battery testing solutions and test methodologies. This background information will form the basis for the next chapter where the high-level design for hardware and software components for an Intelligent Battery Tester will be described.

Chapter 3

Overall system design

The proposed system to determine the health of 12V/7Ah batteries is an Intelligent Battery Tester (IBT). Modularity and simplicity was chosen as the main design philosophy for the IBT, this is to ensure that individual parts of the system can be debugged or replaced separately and easily, without needing detailed knowledge about the design. The following sections will describe the high level design of the hardware and software components.

3.1. Hardware design

Figure 3.1 shows a block diagram of the intended system. It consists of a loading and control circuit with an I/O PCB connecting the two. Each block is intended to be a stand-alone and off the shelf component, with the I/O PCB being the exception. All components of the system will share a common ground connection.

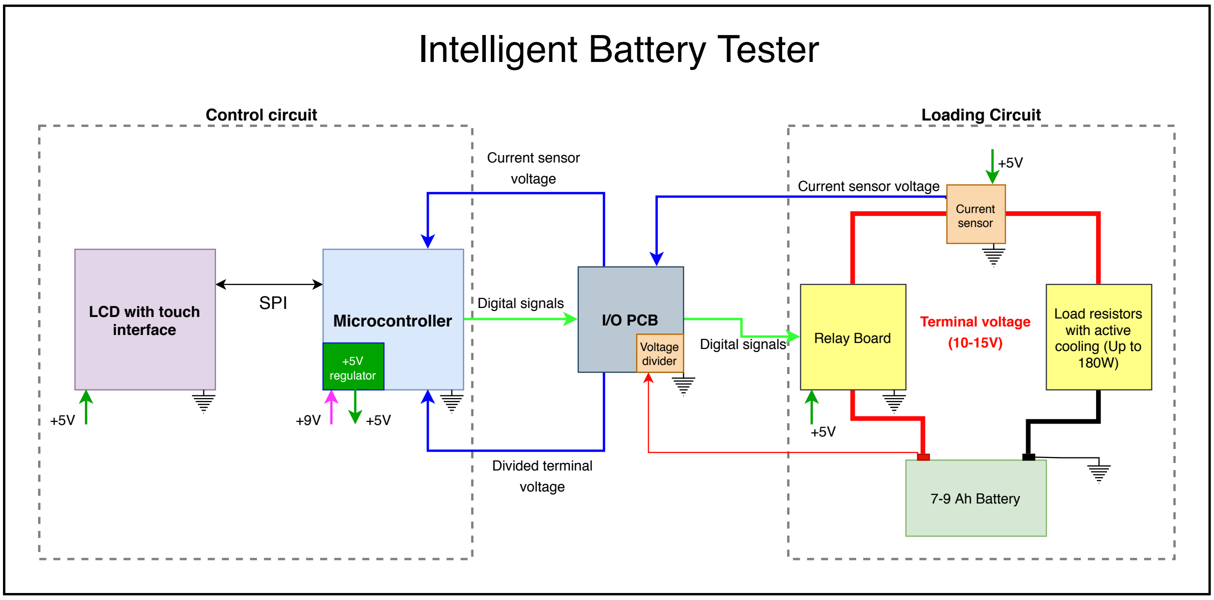

Figure 3.1: System block diagram.

3.1.1. Control circuit

The control circuit will be used to monitor current draw and battery terminal voltage. It is important that these measurements are accurate as all battery metrics measured will be derived from them. The circuit will also control which loads are connected to the battery and will act as a graphical user interface (GUI).

A microcontroller was chosen to handle the logic that manages the control circuit, because it is the most robust and inexpensive way to take the required measurements and control multiple electronic switches (relays). Raspberry Pis were avoided because they are more expensive and have an extra layer of complexity that comes with running an operating system, not to mention the fact that a fully-fledged, 64-bit computer is excessive for this application. Devices like the IBT can be expected to be treated like tools instead of electronic devices, thus having a device that can be unplugged mid-test without risk of corruption, is crucial. Microcontrollers also usually include an onboard +5V linear regulator, which negates the need to build one and add extra complexity.

There are a variety touch-enabled LCDs available for microcontrollers like the Arduino and STM32. These displays are extremely versatile and almost universally compatible, as they plug into the Arduino standard header layout. It allows the user to give touch inputs, which are much less cumbersome to use than the buttons found on most other battery testers. On-screen elements can also be presented in colour and test results can be graphically shown. Library availability is good for these displays and will ease the software development process.

3.1.2. Loading circuit

The loading circuit should subject batteries being tested to currents of up to 15A in order to simulate an average UPS load of around 180W. At this load, a single battery UPS will run for approximately 18 minutes, as can be seen in Figure 3.2 [8]. This time is similar to the 21 minutes achieved in an early test conducted on a basic office PC and monitor connected to a single battery RCT UPS.

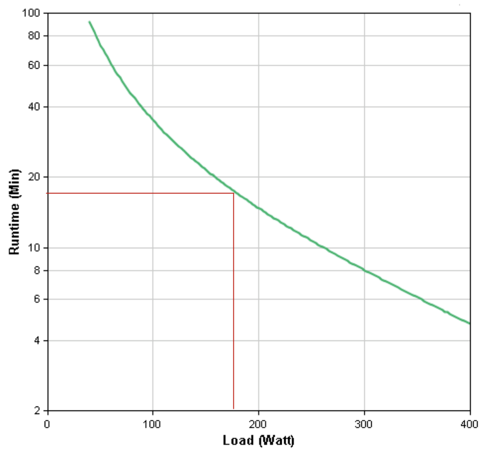

Figure 3.2: Runtimes under load.

A resistive network switched in parallel was chosen to dissipate the power supplied by the battery. Switching of the loads is to be handled by mechanical relays controlled by the microcontroller. In this way, various load levels can be achieved by adding or removing resistors with different values from a parallel configuration. A DC-DC boost converter would be able to achieve the same load currents as switching resistors in parallel, but seeing that a resistor would still be required to dissipate power from the converter, it was decided to simply use resistors. Resistive networks are also more robust, with fewer components that can fail. Active cooling such as a heat sink and fan will be required to dissipate the 180W delivered by the battery.

3.1.3. Signal conditioning and distribution

Signals need to be passed between the control and loading circuitry in order to manage load switching. This necessitates designing a simple PCB that allows signalling between the various components of the system. Load current and terminal voltage signals need to be conditioned before being sampled by the analogue-to-digital converter (ADC) on the microcontroller. Signal conditioning components are to be integrated onto the proposed I/O PCB.

A simple resistive divider circuit was selected to step down the terminal voltage to a level accepted by the microcontroller. Current sensing can be achieved by measuring the voltage drop across a low-resistance shunt, using differential amplifier, but would require designing and calibrating the circuit due to inaccuracies in the manufacturing of these resistors. A pre-calibrated hall-effect current sensor module was chosen for the final design, because this is accurate without calibration and has very low series resistance. These modules can also measure negative currents and still output positive voltages to be read by the microcontroller.

3.2. Software implementation

Software for the IBT will be written in C/C++ since this is best supported by the microcontroller used for the control circuitry. The GUI should be intuitive and easily readable. It is also important that the IBT gives the user information on how tests work and approximately how long they will take. The IBT will be able to abort tests and should give feedback on what it is doing at any point. Test results will be displayed graphically and numerically.

The test protocol is to be designed using a combination of published literature and empirical experimentation. Prior research showed that there may not be a strong enough correlation between parameters that can be measured quickly to accurately predict the health of every battery. Thus two different tests, one rapid and another longer test, are proposed to cover all possible battery ages.

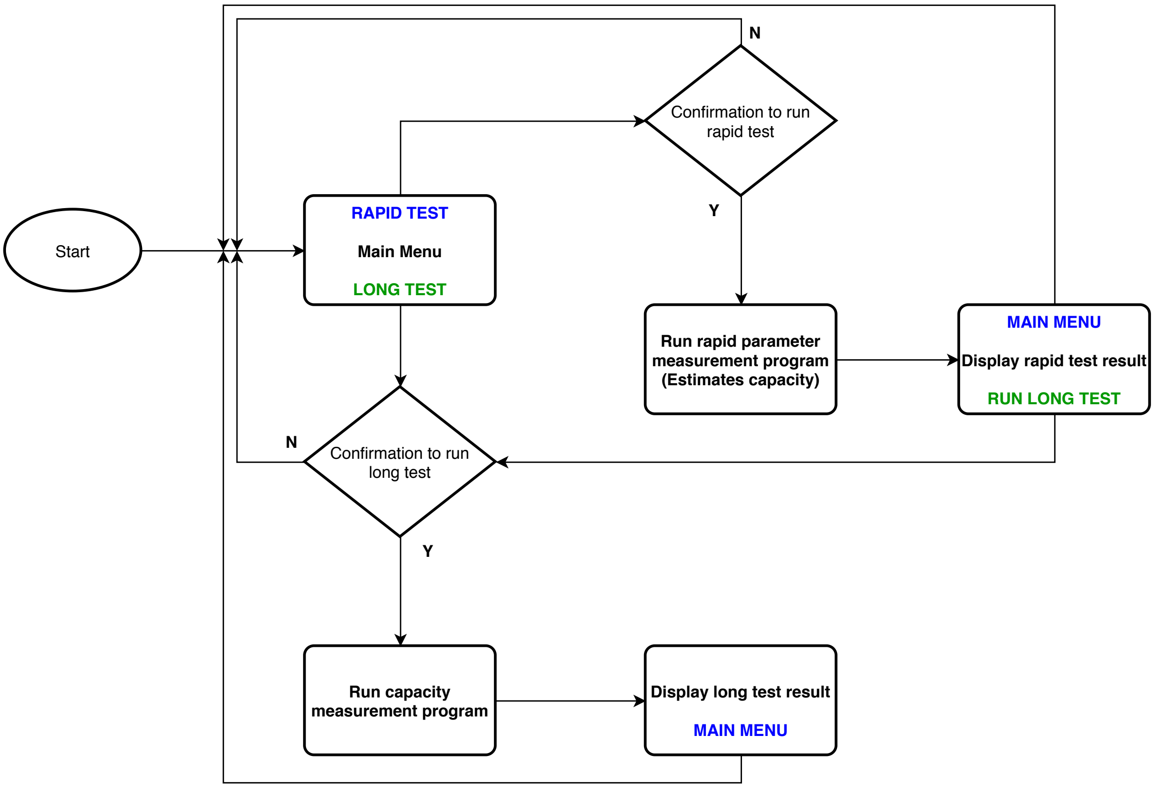

Figure 3.3: A basic flowchart of the intended GUI and test programs.

A flowchart that shows how the GUI is intended to work is shown in Figure 3.3. The details of how the rapid and long test programs are to be conducted is covered in Chapter 5.

3.3. Chapter summary

In this chapter, the high-level design for the hardware and software components of the intended IBT system was discussed. This mainly consisted of detailing the technological choices for addressing the requirements of the IBT. In the next chapter, the detailed hardware design for the IBT is discussed along with a hardware test.

Chapter 4

Detailed hardware design

This chapter will describe the detailed hardware implementation of the hardware components described in Chapter 3. Figure 4.1 shows the final overall system diagram of the IBT. It includes the final component selections for the various parts of the system.

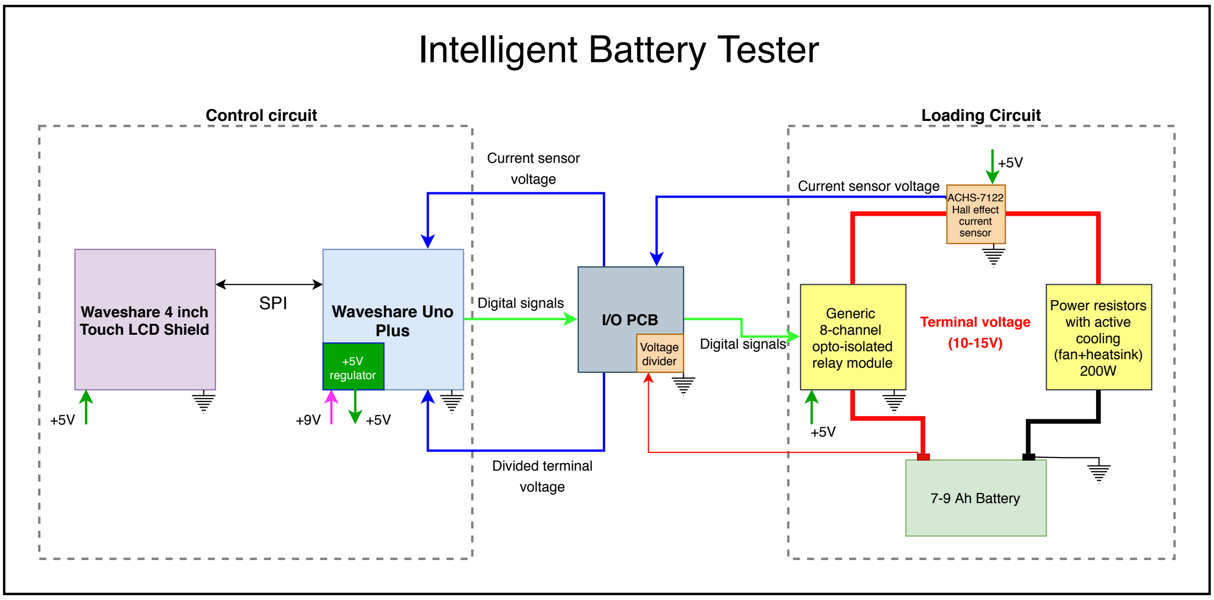

Figure 4.1: Final system diagram.

4.1. Control circuit

The control circuit consists of a Waveshare Uno Plus, which is an Arduino-compatible alternative to the OEM Arduino Uno R3. This version has a few advantages over the standard Uno, such as a laterally mounted reset button and additional solder pads to allow connections to the board even with a shield installed on the headers [9]. These additional pads, highlighted in Figure 4.2, are very important as a 4-inch Waveshare Touch LCD Shield is installed on the Uno Plus's headers which would not allow any other peripheral connections to be made without the additional pads. The Uno Plus is supplied with +9V from an inexpensive switchmode supply and the onboard regulator of the Uno Plus then supplies the rest of the system with +5V via the I/O PCB.

For the GUI, the 4-inch Waveshare Touch LCD Shield was chosen as it is officially

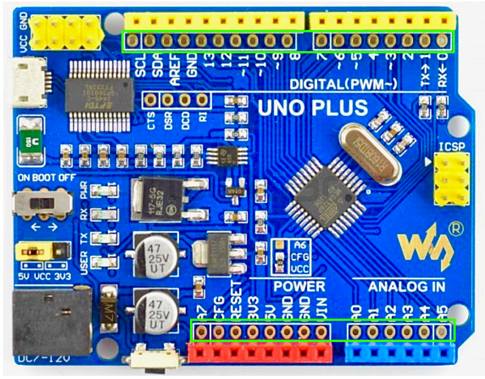

Figure 4.2: A Waveshare Uno Plus, with additional pads highlighted by green borders.

compatible with the Waveshare Uno Plus [10]. This display is also one of the larger ones available for Arduino boards. The LCD Shield gives great flexibility for plotting load curves and allows a much more intuitive user interface to be designed for the IBT, when compared to the non-touch enabled testers available. The Uno Plus uses a SPI interface to control the LCD Shield; this uses fewer digital and analogue pins than similar displays, thereby avoiding the need to buy a more expensive Arduino with more pins, such as the Due. A C/C++ library is included with the LCD Shield and contains functions to draw basic shapes, clear the screen, print text etc. The library also contains a SPI driver for the LCD Shield [11].

4.2. Loading circuit

The loading circuit switching is handled by a generic 8-channel, optically isolated relay module, designed to be powered and driven directly from an Arduino [12]. Power resistors, mounted to a heat sink, are used to dissipate the energy delivered by the battery when loaded. Active cooling in the form of an old PC fan was employed to keep surface temperatures down to avoid causing burns when accidentally touched. The fan is powered from the +9V supply that also powers the Arduino. The heat sink is rated for up to 200W of heat dissipation and is designed to work passively, so a fan failure will not damage the system.

Table 4.1 provides the specifications of the power resistors. The maximum expected load power in Table 4.1 is based on the assumption that the battery maintains approximately 13V at its terminals when placed under load. This will mean that the power ratings of the 1.5Ω and 3Ω power resistors will be exceeded by 13.7% and 12.6% respectively. This was deemed a non-issue because when all power resistors are loaded simultaneously, the terminal voltage of a brand new 12V/7Ah battery drops to well below 12V. If we assume that the battery is able to maintain 12V at its terminals under this load condition, the power delivered to the power resistors will be 180W and will thus never exceed the 200W rating of the heat sink. In all other cases, there is enough heat dissipation headroom for the heat sink to deal with the extra power that would need to be dissipated from the 1.5Ω and 3Ω power resistors.

Model	**Resistance** [Ω]	**Power rating** [W]	**Max hotspot temp.** [°C]	**Maximum expected load power**[W]
RS PRO RS100	1.5±5%	100	200	113.7
Arcol HS50	3±1%	50	250	56.3
Vishay RH050	6±1%	50	250	28.2
Arcol HS15	12±5%	15	200	14.1

Table 4.1: Power resistor ratings.

The loading circuit is designed to draw integer value currents from 0-15A from a 12V source by switching different combinations of L1-L4 in parallel. This will allow the system to place the batteries being tested under a wide variety of load conditions. Current and voltage under these loads will then be plotted graphically by the control circuit. The power resistors are connected to the normally-open contacts of the relay module to protect batteries from over-discharging in case of control circuit failure.

Appendix C shows the detailed design of the loading circuit. The current sensor is included to illustrate where it is measuring current, but the sensor itself is located on the I/O PCB described in Section 4.3. All conductors used in the loading circuit are 12AWG silicone wires to keep resistance as low as possible in the measurement loop. Silicone wires are also more flexible and do not melt like more traditional insulation plastics.

4.3. I/O PCB

An I/O PCB was designed to distribute power to the various sub-circuits of the IBT system. The I/O PCB also houses the voltage divider circuit and current sensor module. The divider circuit consists of a series resistor combination to step down the terminal voltage of the battery to a level that can be sampled by the ADC on the Uno Plus. R_1 is chosen as 10kΩ and R_2 as 3.3kΩ, which will result in 3.72V at the Uno Plus ADC pin at a terminal voltage of 15V according to Equation 4.1. In practice, such high terminal voltages will not occur, thus the 5V limit of the Uno Plus ADC will never be exceeded. The resolution of voltage sensing using the 10-bit ADC on the Uno Plus is calculated in Equations 4.2 and 4.3. A resolution of 19.7mV should be more than adequate for the purposes of the IBT system as this is less than 2% of the expected 12V across the battery terminals. The current measurements should be accurate to within 5% at the lowest load level (1A).

$$V_{pin} = \frac{R_2}{R_1 + R_2} * V_{terminal} \tag{4.1}$$

$$V_{resolution} = \frac{V_{ADCmax}}{2^n - 1} * \frac{R_1 + R_2}{R_1} = \frac{5.02}{1023} * \frac{13.3}{3.3} = 19.7mV \tag{4.2}$$

$$I_{resolution} = \frac{V_{ADCmax}}{2^n - 1} * 10\frac{A}{V} = \frac{5.02}{1023} * 10 = 49.1mA \tag{4.3}$$

The circuit diagram for the I/O PCB can be found in Appendix D. A current sensor module is used to sample current supplied by the battery under load. The module acts as a carrier for the Broadcom ACHS-7122 Hall effect linear current sensor. It has a very low resistance current path (0.7mΩ) and accepts bidirectional current inputs of up to ±20A. The module outputs an analogue voltage proportional to the current, 100mV/A and is centred around 2.5V [13]. The current measurements have a resolution of 49.1mA as calculated in Equation 4.3.

Reverse polarity protection is provided by choosing R_1 as 10kΩ at the ADC pin as this large resistance will limit current flow from the ADC pin, preventing damage.

4.4. Hardware test

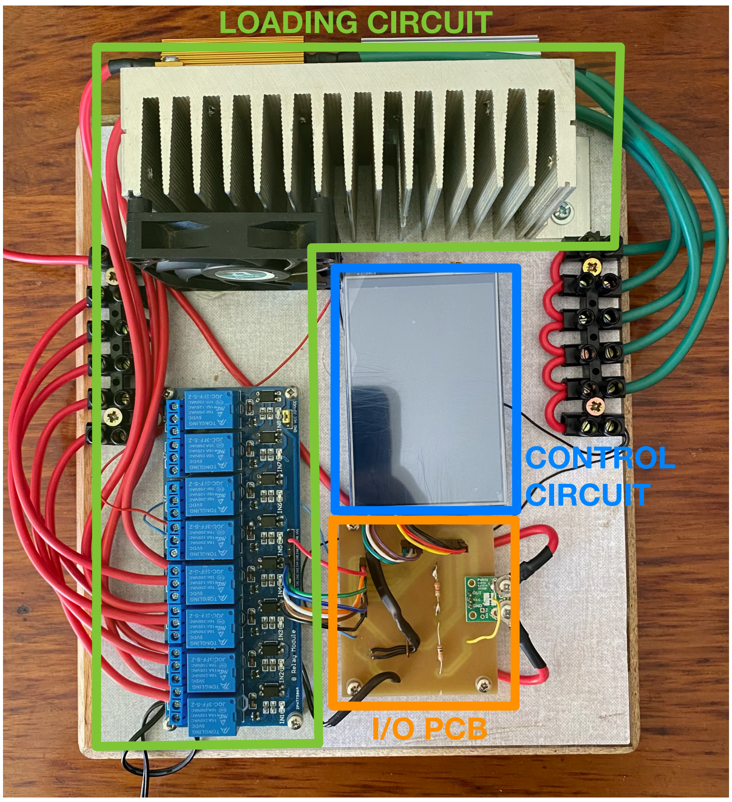

Figure 4.3: IBT final hardware implementation.

After the IBT system was built, a hardware test was performed to ensure that measurements taken by the IBT are accurate and that the system could load batteries without overheating. A simple debugging program was written to allow manual control of load switching for testing purposes. A battery was then placed under a variety of loads, with voltage and current being measured using the IBT and a multimeter. The IBT was calibrated according to measured resistor divider ratios and the voltage-current relationship as provided in the current sensor data sheet [13]. Table 4.2 lists the resulting accuracy measurements. The voltage measurements are very accurate with errors of less than 1% across the whole range. Current measurements are slightly less accurate, but are still within 5% of the multimeter measurements. Overall, the system performs as expected, with errors in line with the resolution limitations as discussed in Chapter 4.3.

Voltage measurements		
Multimeter measurement[V]	**IBT measurement[V]**	**Absolute error**
13.17	13.24	0.5%
12.92	12.97	0.4%
12.50	12.47	0.2%
Current measurements		
Multimeter measurement[A]	**IBT measurement[A]**	**Absolute error**
1.05	1.09	3.8%
5.25	5.24	0.2%
6.72	6.89	2.5%

Table 4.2: Measurement accuracy tests.

Another important measurement is the loop resistance of the loading circuit. A 12V/7Ah battery typically has very low internal resistance of around 22 mΩ. This is about the same resistance as 3 meters of thick, 12 AWG wire. The loop resistance was measured by determining the voltage drop across all conduction paths at known currents. Ohm's law was then applied to calculate the resistance. Table 4.3 lists the results of these measurements. The average loop resistance between the two currents at which the measurements were taken is calculated as 35.7 mΩ. This will be subtracted from the measured internal resistance to determine the true internal resistance of the battery. This can be done because the loop resistance is in series with the battery and therefore its internal resistance.

Measured loop current [A]	**Measured loop voltage drop [mV]**	**Calculated loop resistance[mΩ]**
1.18	41.2	34.92
8.24	300.2	36.43

Table 4.3: Loop resistance measurements.

4.5. Chapter summary

In this chapter, the hardware components were designed/selected and the final system was built. A hardware test was performed to verify that all components were functioning correctly. The next chapter details the software design for the overall IBT system.

Chapter 5

Detailed software design

When designing the test methodology for the IBT, a combination of related research on battery testing and empirical testing was used to determine the viability of the test methodologies outlined in Section 2.3.

5.1. Empirical data collection

Since internal resistance and current-voltage (I-V) characteristics of 12V/7Ah batteries in various states of health are not documented, empirical evaluations were performed using a sample-set of 23 12V/7Ah batteries.

A simple parameter capture program was written and loaded onto the IBT. The data collected by the IBT includes internal resistance as well as I-V characteristics of the battery under various loads. The I-V characteristics were measured by subjecting the battery to a particular load for 10 seconds to allow the terminal voltage to stabilise, then sampling voltage and current values at the end of each period. These measurements are shown in the top half of Figure 5.1 and were used to plot an I-V curve for each battery. The program removes surface charge prior to collecting I-V characteristics and measuring internal resistance.

The parameter capture program also discharged each battery in the sample set, while sampling the power delivered by the battery every second. Numerical integration in the form of a Riemann-sum, as discussed in Section 2.3.2, is then used to calculate the energy delivered until a cut-off voltage of 10.8V is reached. This total energy was the capacity (in Wh) of the particular battery. This method is usually referred to as coulomb counting and is an accurate way to measure battery capacity. This same method is used for the capacity test discussed in Section 5.2. The cut-off voltage was chosen to be slightly higher than the 10.5V minimum voltage most UPS's impose before shutting down [8], in order to avoid the UPS not charging the battery after this discharge. A 1C discharge rate was chosen as this should result in a total discharge time of around 40 minutes for a brand new battery, according to the discharge curve in the data sheet [3].

A higher discharge rate was avoided due to higher temperatures this would lead to on the heat sink, which became quite uncomfortable to the touch at 1.5-2C. Figure 5.1 shows the parameter capture program after collecting data from a battery.

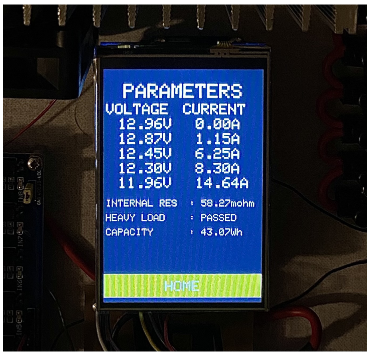

Figure 5.1: Data capture program result.

In this way a dataset of 23 sets of measured 12V/7Ah battery parameters, namely internal resistance, I-V characteristics and capacity was compiled to aid in designing a rapid test for the IBT. This data was then used to plot I-V curves (from the measured I-V characteristics) and investigate the relationship between internal resistance and battery capacity. The terms "I-V curves" and "I-V characteristics" are used interchangeably from this point. The full dataset can be seen in Table 5.1. The "Load test pass?" column in Table 5.1 is based on how closely the I-V characteristics of the specific battery in the data set follows that of a nominal 12V/7Ah battery. The details of how this is calculated are covered in Section 5.3.1. I-V curves for the full data set were also plotted, but carry little meaning due to the amount of data that needs to be displayed and was omitted from this document. A few I-V curves from the dataset are discussed and shown in Section 5.3.

Battery number	Rated capacity [Wh]	Measured capacity [Wh]	Measured internal resistance [mΩ]	Load test pass? [YES/NO]
1	50	43.1	23.4	YES
2	50	15.2	37.3	NO
3	50	10.7	67.7	NO
5	50	17.9	36.9	NO
6	50	6.4	36.9	NO
7	50	14.2	33.5	NO
8	50	13.8	54.7	NO
9	50	11.2	63.6	NO
10	50	45.8	26.6	YES
11	50	20.8	32.6	NO
12	50	15.8	53.6	NO
13	50	13.8	50.0	NO
14	50	14.5	36.4	NO
15	50	15.0	41.1	NO
16	50	14.6	36.2	NO
17	50	13.5	40.6	NO
18	50	13.1	47.1	NO
19	50	15.9	34.8	NO
20	50	14.0	54.8	NO
21	50	53.7	16.0	YES
22	50	57.7	15.2	YES
23	50	61.5	20.5	YES

Table 5.1: Full dataset of collected 12V/7Ah parameters.

5.2. Capacity test

A brand new 12V/7Ah battery has an energy capacity of approximately 50Wh when discharged to a terminal voltage of 10.8V (1.8V/cell) as stated in the constant power curve in the data sheet [3]. Exact capacity values differ between battery brands, but higher quality units are all rated in the range of 48-52Wh at the discharge rate/cut-off voltage combination chosen for the IBT.

The capacity test as implemented in the IBT system acts as a last resort if the rapid test is inconclusive. This test is referred to as the ”full test” on the IBT. The capacity test discharges the battery under the conditions as discussed in Section 5.1. This test will always be conclusive and accurate, but takes much longer (up to 40 minutes) than the 3 minutes required by the load and internal resistance tests. The full test (capacity test) is considered the gold standard for measuring battery health and will be the benchmark against which the results of the rapid tests, discussed in Section 5.3, are measured. The usefulness of the capacity test does, however, stretch further than simply testing aged batteries as it can also be used to identify the best brands of new batteries and even underperforming ones.

5.3. Rapid test

A rapid test methodology for the IBT was designed based on a combination of a load test and an internal resistance test. The load test evaluates how closely a measured battery's I-V curve follows that of a known new battery. The internal resistance test simply measures the DC internal resistance and makes the same comparison. The IBT will give a "PASS/FAIL" result for the load and internal resistance tests based these comparisons. The details of this are discussed in Sections 5.3.1 and 5.3.2. If a battery passes both tests, a "GOOD" health rating is given and if the battery fails both tests, a "BAD" health rating is given.

The IBT will deem a rapid test to be inconclusive if a battery passes only one of the tests and will recommend to the user to run the full capacity test as described in Section 5.2, which can accurately measure remaining battery capacity. The limitation of the full test is that it can take up to 40 minutes to run for newer batteries. An 80% remaining capacity threshold was chosen based on recommendations in the literature [1, 7] that lead acid batteries have a workable bandwidth of 80-100% remaining capacity before needing to be retired. This is due to the known rapid drop-off in capacity once the 80% threshold is reached.

5.3.1. Load test

Figure 5.2 gives valuable insight into the correlation between measured remaining capacity and load I-V characteristics. When considering the information in our collected dataset, it became quite obvious that batteries must perform extremely close to a nominal battery to pass the load test. The I-V curve for the nominal battery was created by averaging the I-V curves obtained from three known new batteries. The load test evaluates how far the terminal voltage of the battery drops below that of the nominal battery I-V curve at any of the current levels demanded by the load test.

By choosing a cut-off of 2% below the terminal voltage of the nominal I-V curve for passing the load test, all batteries below 80% remaining capacity in our sample set are correctly identified.

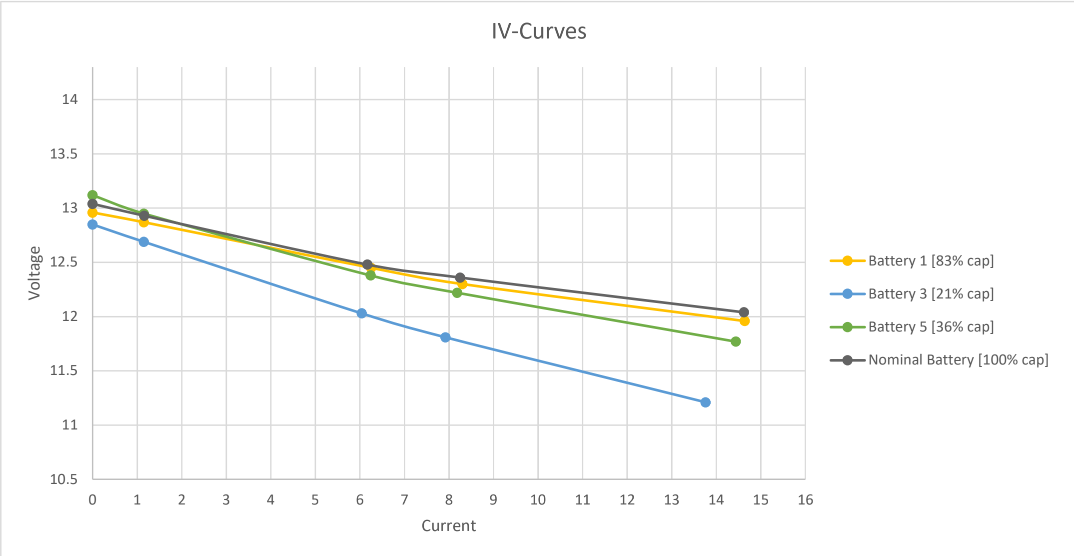

Figure 5.2: I-V curves measured for batteries in various states of health.

5.3.2. Internal resistance test

The internal resistance test for the IBT is based on the guidelines outlined in the IEC 61951-1:2005 standard [1]. The rule of thumb, as suggested by Glenn Albér [7], that batteries with internal resistance values 25% above nominal will usually fail a capacity test (less than 80% of nominal capacity remaining) proved to apply to our dataset. The 80% remaining capacity and 125% internal resistance thresholds are shown by the green and pink lines in Figure 5.3 respectively. From this it is clear that the internal resistance test will also correctly identify all batteries in our dataset and confirms that Glenn Albér's rule of thumb is fairly accurate.

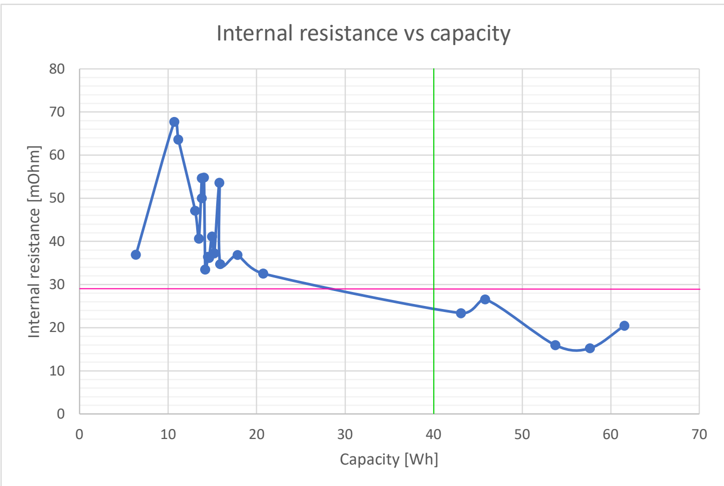

Figure 5.3: Internal resistance plotted against capacity for the 23 batteries in the sample set.

5.4. Graphical User Interface

The software that runs on the IBT is designed to give the user as much information as possible, avoiding one of the limitations of other battery testers. This includes descriptions of what the various tests do, how long a specific test will take and gives the user continuous feedback while conducting a test. Battery statistics such as voltage, current and power are displayed while tests are running, allowing the user to see if anything goes wrong and lets the user abort tests early. Figure 5.4 shows a flow diagram of the final software implementation for the IBT.

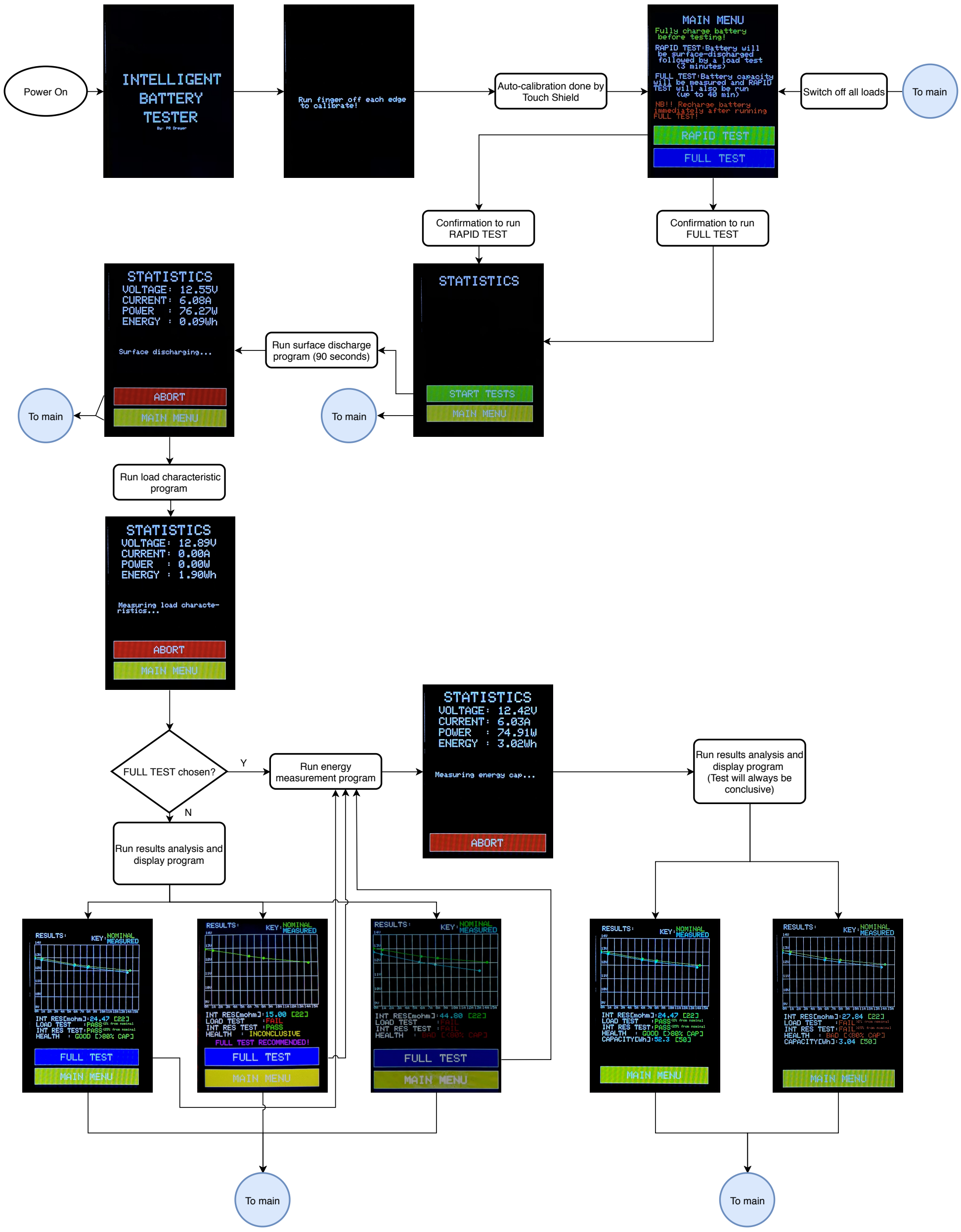

Figure 5.4: Final software implementation flow diagram.

5.5. Chapter summary

This chapter first describes how a dataset of parameters for batteries in various states of health was collected. Details of how the full test will be conducted to measure capacity is given, followed by the design of rapid test protocol using a combination of empirical experimentation and existing methodologies. The chapter also shows the final implementation of the GUI. In the next chapter, the viability of the rapid test protocol is discussed.

Chapter 6

Results

6.1. Results for compiled data set

The methodologies implemented in the final software for the IBT were applied to our dataset. Comparisons between the full and rapid test results are summarised in Table 6.1. The tests were not practically conducted a second time, but the dataset was used to infer what the result would have been had the final software been used. The IBT identifies batteries with below 80% remaining capacity as "BAD" and ones above 80% as "GOOD".

Battery	Rapid test rating [GOOD/BAD/ Inconclusive]	Nominal Capacity [Wh]	Full test result (capacity remaining) [Wh]	Percentage of nominal capacity	Rapid test accurate? [YES/NO]
1	GOOD	50	43.1	86%	YES
2	BAD	50	15.2	30%	YES
3	BAD	50	10.7	21%	YES
5	BAD	50	17.9	36%	YES
6	BAD	50	6.4	13%	YES
7	BAD	50	14.2	28%	YES
8	BAD	50	13.8	28%	YES
9	BAD	50	11.2	22%	YES
10	GOOD	50	45.8	92%	YES
11	BAD	50	20.8	42%	YES
12	BAD	50	15.8	32%	YES
13	BAD	50	13.8	28%	YES
14	BAD	50	14.5	29%	YES
15	BAD	50	15.0	30%	YES
16	BAD	50	14.6	29%	YES
17	BAD	50	13.5	27%	YES
18	BAD	50	13.1	26%	YES
19	BAD	50	15.9	32%	YES
20	BAD	50	14.0	28%	YES
21	GOOD	50	53.7	107%	YES
22	GOOD	50	57.7	115%	YES
23	GOOD	50	61.5	123%	YES

Table 6.1: Comparison of results of rapid and full tests for the compiled dataset.

6.2. Results for previously unseen batteries

A sample of 3 additional (NS1-NS3), previously untested 12V/7Ah batteries was collected. The final hardware and software implementation for the IBT was used to perform a rapid test on this sample, followed by a full test. The results were then compared to gauge how viable the rapid test is for quickly identifying batteries that have aged. Table 6.2 summarises the results of the full and rapid tests.

Battery	**Rapid test rating** [GOOD/BAD/ Inconclusive]	**Nominal Capacity** [Wh]	**Full test result (capacity remaining)** [Wh]	**Percentage of nominal capacity**	**Rapid test accurate?** [YES/NO]
NS1	BAD	50	6.6	13%	YES
NS2	GOOD	50	44.8	90%	YES
NS3	BAD	50	21.8	44%	YES

Table 6.2: Comparison of results of rapid and full tests for three previously unseen batteries (NS1-NS3).

6.3. Chapter summary

The rapid test protocol correctly predicted battery health for the small sample set of previously unseen batteries and also correctly predicted battery health for our original sample set considered in Tables 6.1 and 6.2. Arguably, batteries closer to the threshold would have proven valuable members of the data set. Due to the difficulty of knowing how aged a battery is before testing, it is hard to find specific samples that have 60-80% capacity remaining.

Chapter 7

Summary and conclusion

The work in this project began by investigating existing battery testing solutions for generic 12V/7Ah batteries and their limitations. The health of these batteries are often hard to determine, due to the limited information given by existing battery testers. Some existing test methodologies for lead acid batteries were also investigated to aid in designing an Intelligent Battery Tester. Hardware and software was designed and implemented to allow voltage and current to be measured over time for a programmable load. The final software implementation and GUI was designed to be intuitive to use and gives the user as much information as possible, avoiding one of the limitations of other battery testers.

The IBT was first used to collect the data on I-V characteristics, internal resistance and battery capacity for a set of 23 batteries in various states of health. This data set was used to confirm the methodologies and recommendations made in the literature. It was also used to design an empirical test methodology based on the analysis of I-V characteristics (aka load test), as data on such a test for 12V/7Ah batteries could not be found in the literature.

The IBT can run a full test that uses coulomb counting to directly measure the capacity of a battery and takes up to 40 minutes to complete. The full test will always be conclusive and was used as a benchmark to evaluate the accuracy of the rapid test. A rapid test program was developed that uses the results of the internal resistance and load tests to estimate the state of health of a battery in 3 minutes. When a rapid test is inconclusive, the IBT will recommend running the full test.

The rapid test proved accurate for all batteries in our dataset as well as for three previously untested batteries. The functionality of the IBT extends further than simply testing aged batteries, because the full test can also be used to identify the best performing brand and model of new 12V/7Ah batteries. The project was deemed successful overall thanks to the IBT's ability to rapidly identify "definitely good" or "definitely bad" batteries, while also costing a similar amount, approximately R2000, to build when compared to other consumer battery testers.

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Appendix A

Project Planning Schedule

Month	Day	Work to be done
July	27	Conduct some background research on battery testing and 12V/7Ah batteries
August	3	Conduct some background research on battery testing and 12V/7Ah batteries
	10	Design hardware elements for IBT
	17	Finalise design of IBT and order components
	24	Design I/O PCB
	31	Break from skripsie
September	7	Manufacture I/O PCB and finalise assembly of the IBT system
	14	Perform hardware test and start data collection for empirical test methodology
	21	Finalise data collection and implement final software
	28	Testing with final software
October	5	Write report: Do report outline and start related work
	12	Write report: Finish related work
	19	Write report: System and detailed design sections
	26	Write report: Results, introduction and conclusion sections
November	2	Write report: Implement feedback from supervisors and write abstract
	9	Hand-in

Appendix B

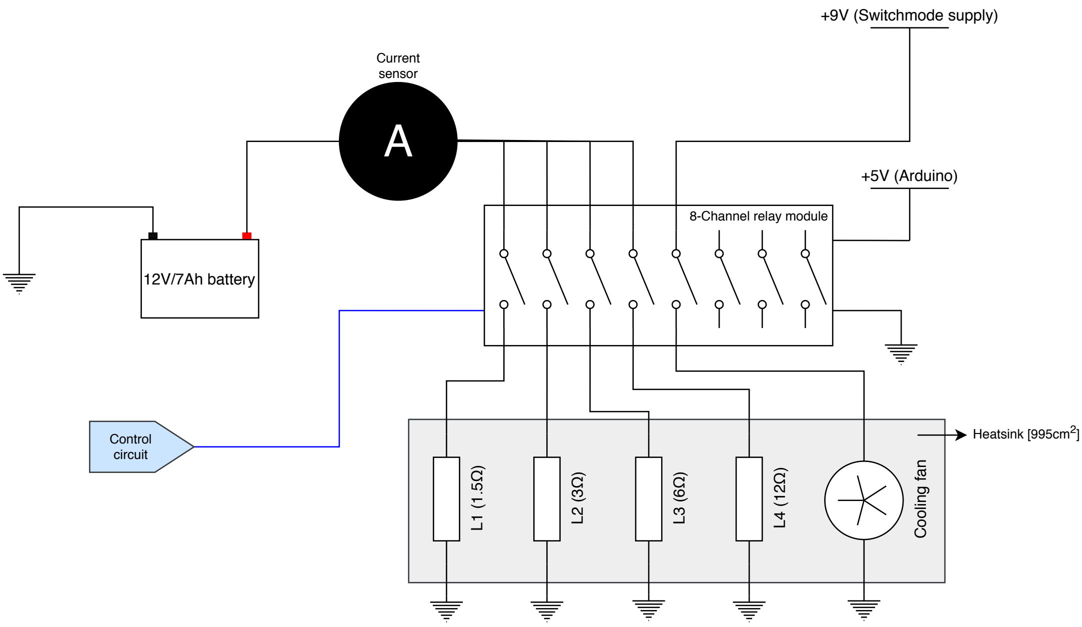
Outcomes Compliance

ECSA Outcome	Motivation
ELO 1. Problem solving: Identify, formulate, analyse and solve complex engineering problems creatively and innovatively.	Chapter 2 involves identifying limitations of existing battery testing solutions. It also involves identifying required background information on test methodologies that are used to set objectives that will allow the problem of testing 12V/7Ah to be solved. Chapters 3, 4 and 5 involved hardware and software design to meet the objectives set for the project.
ELO 2. Application of scientific and engineering knowledge: Apply knowledge of mathematics, natural sciences, engineering fundamentals and an engineering speciality to solve complex engineering problems.	Application of engineering knowledge is exhibited in Chapter 2, 4 and 5, specifically 2.2.2, 4.2, 4.3 and 5.4 as these sections involve understanding hardware limitations, application of mathematical knowledge and embedded programming. Fundamental knowledge of electricity and electronic circuits are used throughout Chapters 2, 3, 4 and 5.
ELO 3. Engineering Design: Perform creative, procedural and non-procedural design and synthesis of components, systems, engineering works, products or processes.	Chapter 3, 4 and 5 include engineering design throughout. Creative solutions are presented to place batteries under realistic loads in a simple way and a more intuitive UI for a battery tester was designed. The selection and assembly of compatible components also exhibits the ability to perform engineering design.

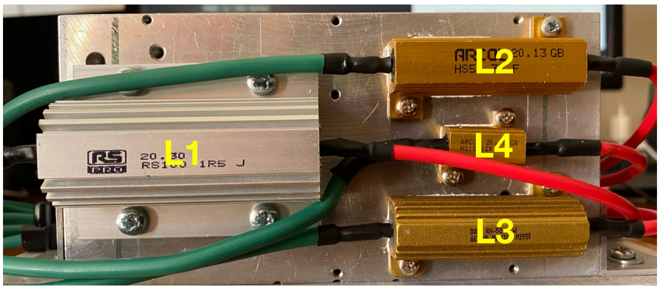
ELO 4. Investigations, experiments and data analysis: Demonstrate competence to design and conduct investigations and experiments.	Chapter 5.1 shows empirical data collection and analysis used to design a test methodology for the IBT system. Chapter 4.4 also includes experiments to ensure the IBT system is able to take accurate measurements.
ELO 5. Engineering methods, skills and tools, including Information Technology: Demonstrate competence to use appropriate engineering methods, skills and tools, including those based on information technology.	Chapter 5.4 required embedded programming knowledge as it deals with peripheral control, GUI design and analogue sampling in C/C++. The use of a multimeter to verify voltage and current measurements in Chapter 4.4 exhibits the ability to use engineering tools. Finally, KiCad was used to design the I/O PCB, which also contributes to the use of engineering tools and skills in this project.
ELO 6. Professional and technical communication: Demonstrate competence to communicate effectively, both orally and in writing, with engineering audiences and the community at large.	The entirety of the report was written in a professional language aimed at a technical/engineering audience.
ELO 8. Individual work: Demonstrate competence to work effectively as an individual.	The whole project was done as an individual, this includes background research, hardware and software design, empirical experimentation and the write-up of this report.
ELO 9. Independent Learning Ability: Demonstrate competence to engage in independent learning through well-developed learning skills.	Chapter 2 involved combining existing knowledge with published research to gain a greater understanding of what battery testing entails, what standard tests already exist and learning about the limitations of various test strategies. This knowledge, especially surrounding lead-acid batteries, was outside the scope of what was learned before starting this project.

Appendix C

Loading circuit design



(a) Loading circuit design



(b) Mounted power resistors

Figure C.1: Load circuit design and implementation

Appendix D

I/O PCB design

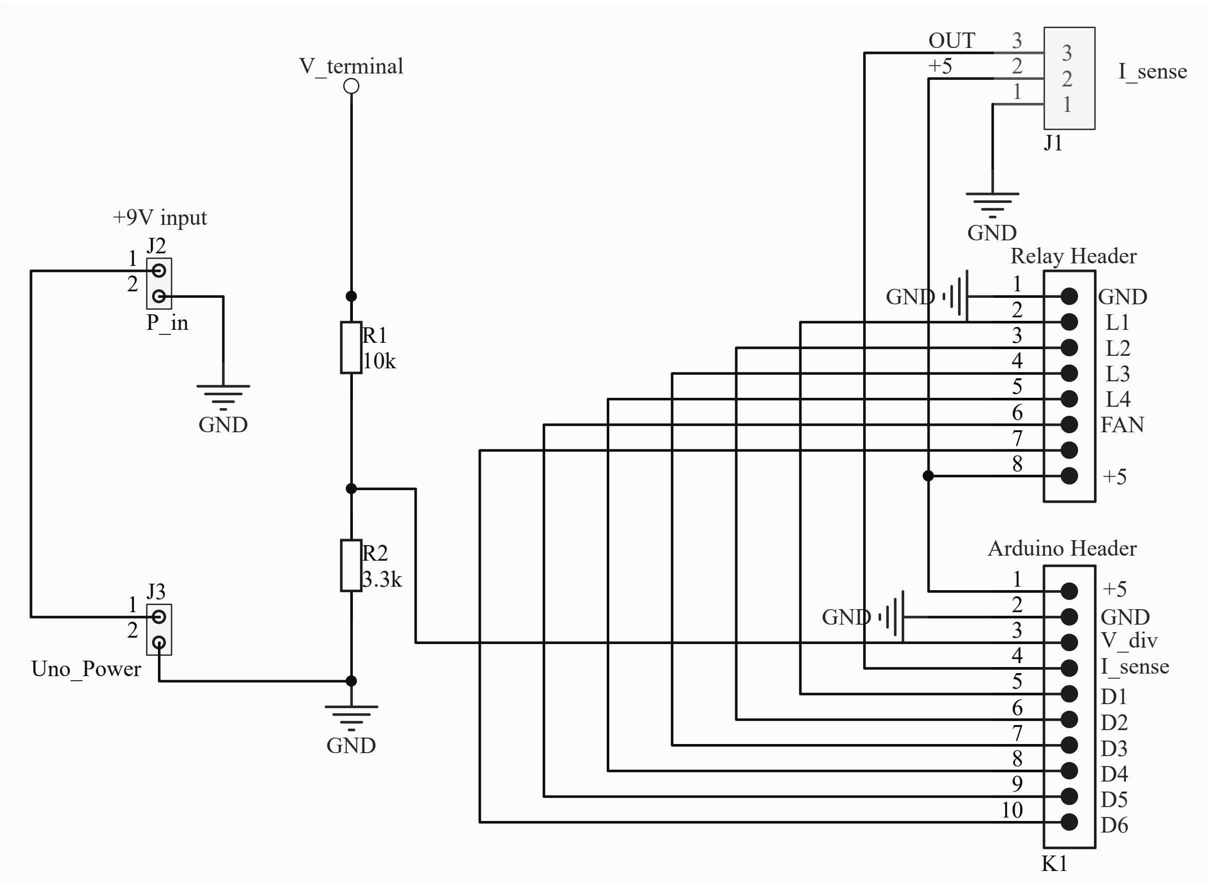


Figure D.1: I/O PCB circuit diagram