Instrumentation Final Report

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1 Schematic Changes

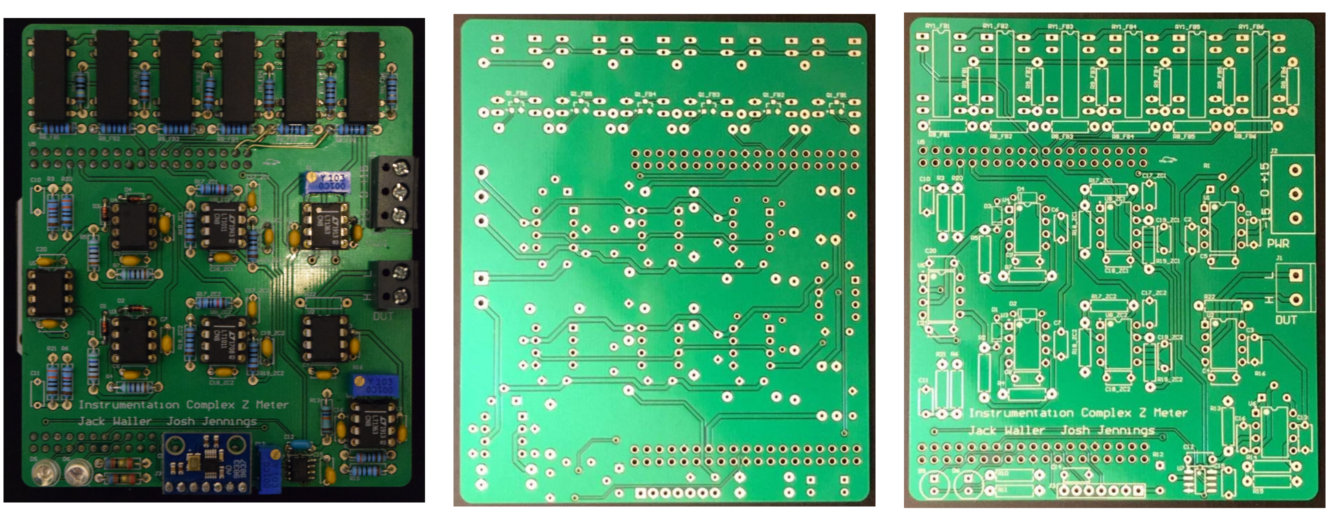
After receiving the prototype boards, it was realised there was a conflict between two of the GPIO used to switch the reference impedance and the pins used for the ST-Link debugger. By cutting traces on the board and using mod wires (seen in the top right of figure 1a) connected to FB5 and FB6 this allowed these signals to be moved to other GPIO pins avoiding the conflict and enabling debugging of the board.

During initial testing of the input stage it also became apparent the AD817 used as a driver for the DUT had an offset on the output which was not possible to null using the offset nulling potentiometer, as the high impedance of the filter used before the driver stage and the input bias current caused around 100mV offset even after nulling. This caused issues with the accuracy of the zero crossing outlined in section 4.3. It could have been remedied by using a lower impedance on the stage before this however since socketed ICs were used it was easier to swap to a driver amp with lower input bias current. Switching to the LT1363 allowed the offset to be cancelled to around a few hundred micro volts, whilst maintaining the capacitive drive capability and the high output current.

Another issue was caused by the solder joints on the through hole components interfering with the ST board below. This became an issue when the reset button was held down by the mounted PCB, thus making the board not run. This was fixed by simply removing the plastic caps from the reset and user buttons.

In between the PCB design being sent and the PCB arriving, a mistake was noticed in the zero-crossing detector. This meant that the feedback resistor was connected to the inverting input not the non inverting, which would have not allowed the circuit to function as expected. However after reviewing the data sheet it was noticed that the pin numbering on the symbol was also wrong, and thus the incorrect schematic was inadvertently correct.

2 Photograph of Prototype



(a) Photograph of Assembled PCB. (b) Underside of bare PCB. (c) Topside of bare PCB.

Figure 1: Photographs of the PCB.

3 Input and Output Signals

In order to use the board, connections must be made to an external power supply, a PC and the DUT. The connections are all made on the right side of the board.

3.1 Analog I/O Signals

The main power connection to the board consists of a ±15V supply. Additional 5V and 3.3V supplies for the MCU and some signal generator components are provided by the MCU breakout board.

The DUT connector provides a high and low side terminal, the high where the excitation signal is present and the low which forms a virtual ground terminal. The PCB makes use of Kelvin connections to the pins of this terminal block, preventing issues due to voltage drop when driving low impedance DUTs.

The micro-controller has 4 main input signals representing an average rectified value of both the voltage drop and current through the DUT, and two square waves representing the zero crossings of these wave forms.

The outputs of the micro-controller are the 6 GPIO used to control reference resistor switching, SPI outputs for control of the AD9833 waveform generator and PGA, and 2 GPIO used for status LED outputs. Figure 2 shows the signal output of the function generator stage of the circuit, and demonstrates how the PGA can be used to generate a variable excitation level. This excitation level can be used to reduce the output current of the signal generator when driving a low test impedance.

3.2 Embedded and companion Software I/O

A companion desktop application that is used to configure the desired parameters while making the measurement. It is written in C# and has been designed to take the information from the user and sends the relevant commands over UART to the micro-controller. It also receives messages over UART from the micro-controller and presents the measurements to the user.

The messages that are used to set the micro-controller parameters are sent over UART. These messages consist of a 12 byte packet containing: a header containing a message delimiter; length information and a message ID; 8 data bytes; and finally a single byte checksum, consisting of the XOR of the 11 preceding bytes, used for error checking. This message structure is also used to transmit data in the form of magnitude and phase values back to the desktop application.

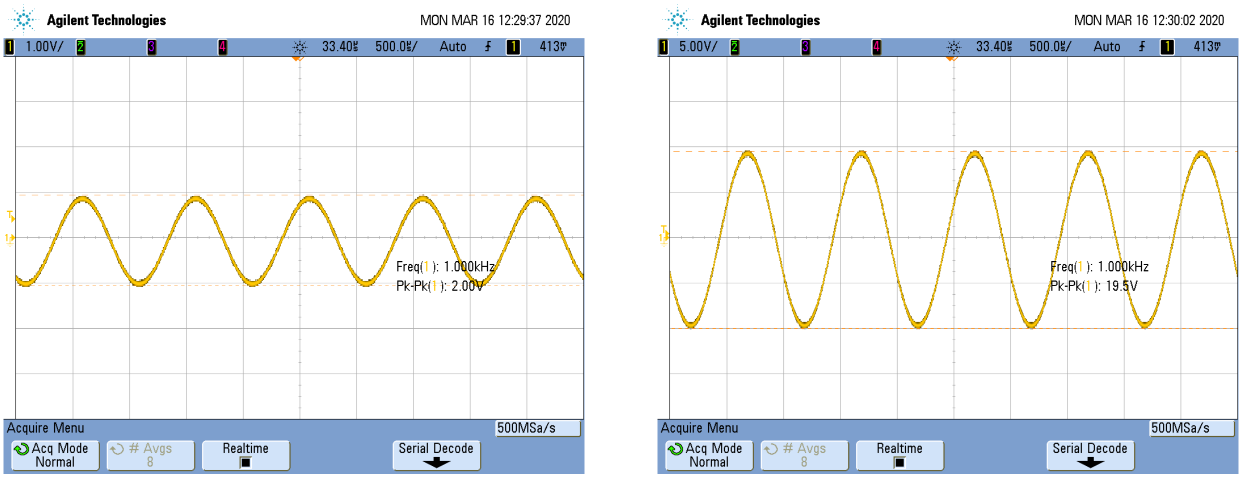
The various messages sent between the application and the micro-controller are are specified as follows:

Byte	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
	0xFF	ID	DLC	Data0	Data1	Data2	Data3	Data4	Data5	Data6	Data7	Checksum
Status r	0xFF	0x01	0x08	Sys	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Checksum
Measure t	0xFF	0x02	0x08	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Checksum
Measure r	0xFF	0x03	0x08	Mag 0:	Mag 4:	Phase 0:	Phase 4:	Vref 0:	Vref 4:	Rref 0:	Rref 4:	Checksum
Set Freq	0xFF	0x04	0x08	Freq 0:	Freq 4:	Freq 8:	Freq 12:	Wave 0	Wave 4:	Wave 8:	Wave 12:	Checksum
Set PGA	0xFF	0x05	0x08	Gain	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Checksum
Set Rref	0xFF	0x06	0x08	Relay	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Checksum
Auto on	0xFF	0x07	0x09	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Checksum
Auto off	0xFF	0x08	0x10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Checksum
Range X	0xFF	0x09	0x11	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Checksum

4 Specifications Achieved

4.1 DUT Excitiation Stage

Initial testing of the device's excitation stage showed that the AD9833 and programmable gain amplifier functioned as expected, and were capable of producing a sinusoidal signal at the frequencies required in the specification. The range of excitation frequencies outputted from the signal generator are shown in figure 2 and 3.



(a) 2.0V peak to peak excitation signal

(b) Full Scale output of signal generator

Figure 2: Signal on DUT High with varying PGA gains

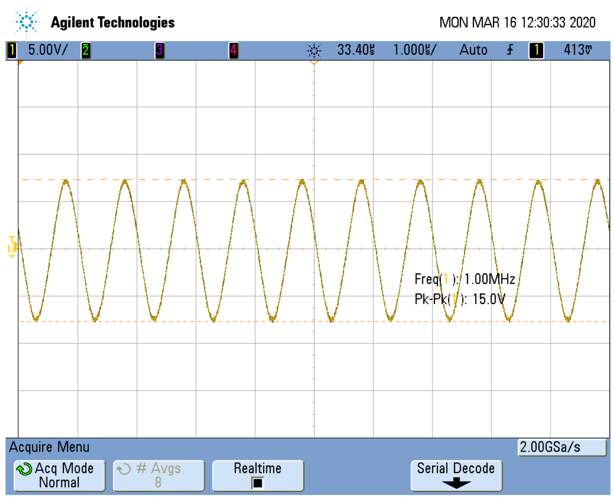


Figure 3: Signal Generator Stage outputting 1MHz waveform

4.2 Auto-Balancing Bridge

While testing the auto balancing bridge stage, it was realised that certain combinations of feedback resistor and DUT caused significant oscillations shown in figure 4, however by connecting a small capacitor in parallel with each feedback resistor the magnitude of the oscillation was significantly damped thus not significantly degrading the performance of the bridge.

4.3 Zero Crossing Detection

The zero crossing detector works as a comparator with 0V as the reference. A small amount of hysteresis is used to prevent parasitic switching due to noise or oscillation on the signal. The output of the zero crossing detector is shown in figure 5a. The offset issue discussed caused an issue with the zero crossing detection shown in figure 5b. This shows the rising edge being delayed as the waveform is compared with 0V but it has an offset. This issue can be mitigated as much as possible by attempting to remove the offset from the input waveform from the zero crossing detector. This could also have been fixed by calibrating the zero crossing detector reference level to the offset of the input waveform, this would have enabled input waveforms with a deliberate DC offset to be used as well, enabling measurement of polarised components.

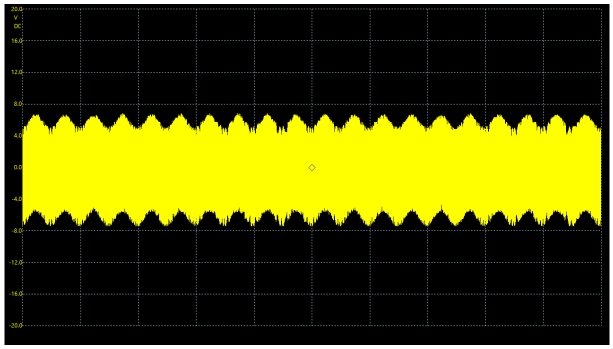
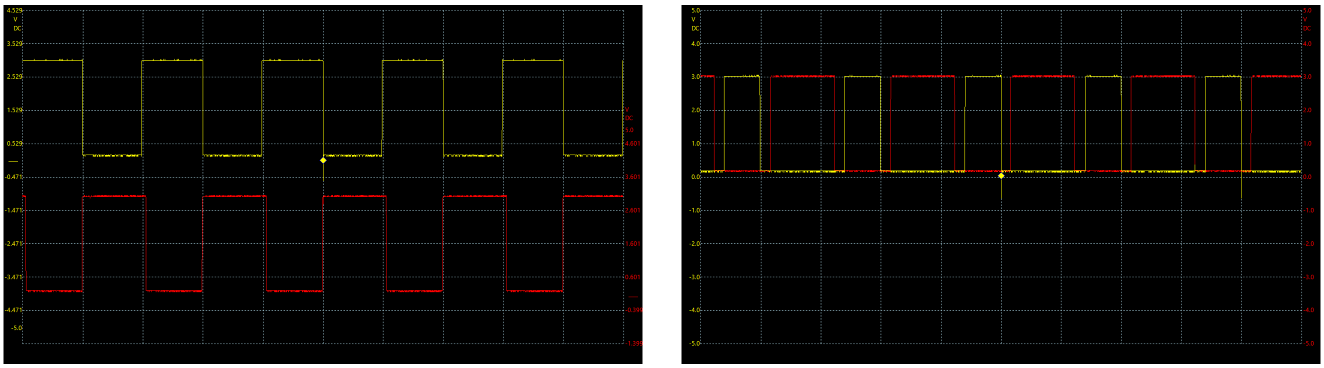


Figure 4: Oscillating output of Auto-Balancing Bridge



(a) Output of Zero Crossing Detector

(b) Output of ZC detector if input waveform has offset

Figure 5: Phase Detection Waveforms

4.4 Precision Rectifier

The precision rectifier stage input and output are shown in figure 6. This shows the rectifier working without degrading the signal significantly, however on the positive to negative zero crossing of the signal a minor glitch can be observed. This was assumed to be due to the op-amp having to slew by the diode voltage drop and thus the relatively low slew rate of the TL072 caused a degradation in performance. An improvement to the precision rectifier would be achieved using an op amp with higher slew rate. This situation was simulated and shown in section 5.1.

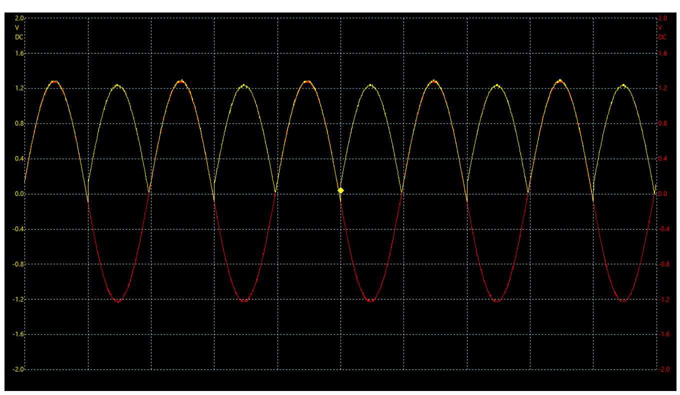


Figure 6: Input (Red) and Output (Yellow) of Precision Rectifier

5 Simulations

5.1 Precision Rectifier

While designing the PCB, simulations were performed on the precision rectifier to verify the operation of the design. After building on breadboard these simulations were revisited in order to investigate a 'glitching' that was occurring on the positive to negative zero crossing.

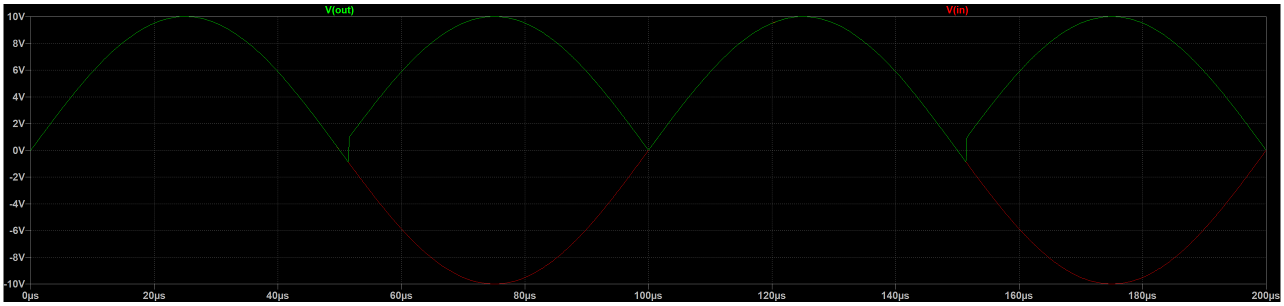


Figure 7: Simulated Output of Precision Rectifier with TL072

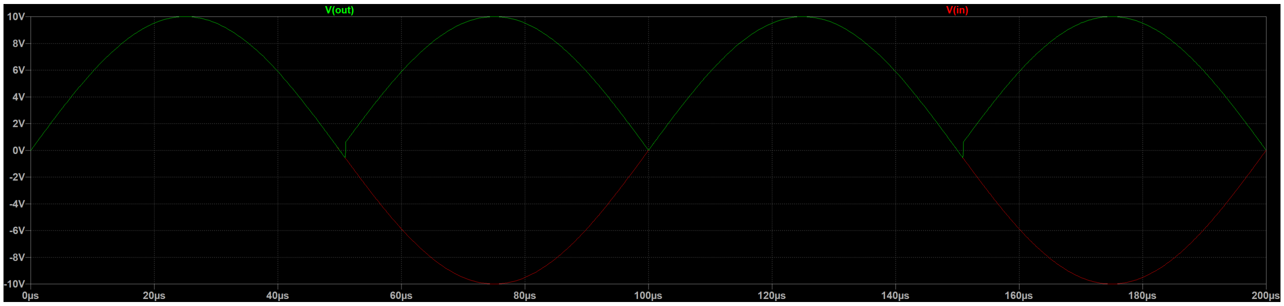


Figure 8: Simuated Output of Precision Rectifier with TL052

The result of the simulations for the TL072 op-amp are shown in figure 7 which show a 'glitch' of approximately 2V in amplitude on the positive to negative zero crossing. This was then rerun for a TL052 op amp with a higher slew rate, and the result of the simulation is shown in figure 8. This shows an improvement in reducing the glitch to an amplitude of 1V. Further increasing the amplifier slew rate made minimal improvements to reducing the amplitude of the glitch and thus the TL052 was decided as a good alternative. Further improvements could have been made by making used of Schottky diodes and thus taking advantage of the lower voltage drop by reducing the amount the op amp has to swing at each zero crossing.

6 BOM and Costs

Category	Item	Quantity	Price Each (£)	Total (£)	Note
IC's	AD9833 Breakout Board	1	1.34	1.34	Purchased from China reseller
	MCP6S21	1	0.852	0.852	
	AD1363	2	4.5	9	
	LT1011	2	2.44	4.88	
	TL072	3	0.52	1.56	recycled from Lv1 'preloved' components bin
	AD622	1	6.3	6.3	
Relays	HE721A0510	6	1.32	7.92	
Other Semiconductors	LEDs	2	0.3	0.6	Used components already owned by Jack
	1N4148TA switching diode	4	0.1	0.4	
	BC850BLT1G	6	0.008	0.048	
Passives	Fixed Resistors (1% tolerance 1/4W Metal Film)	31	0.05	1.55	used stock from Lv1 and ICRS
	Ceramic Capacitors	21	0.05	1.05	used stock from Lv1 and ICRS
	Bourns 3296 10K trim potentiometer	3	1.93	5.79	
Connectors	RS Pro 3 Way Terminal Strip	1	0.42	0.42	
	RS Pro 2 Way Terminal Strip	1	0.4	0.4	
	38 Way 2 Row Board To Board Connector	2	2.14	4.28	
	6 Way 1 Row Board To Board Connector	1	0.44	0.44	
	8 Way DIP Socket	8	0.39	3.12	
TOTAL				**49.95**	

Table 1: BOM for Assembled Board

7 Algorithm

7.1 High Level Description of MCU Code

Controlling the PGA and AD9833: The programmable amplifier is connected to the micro-controller unit via a Serial Peripheral Interface. The gain of the PGA can be set to 1, 2, 4, 5, 8, 10, 16, or 32 by modifying the register value in the PGA. A switch statement is used to calculate which value the PGA should be set to and then the SPI enabled GPIO pins are used to tell the PGA to set it's internal gain.

The same technique is used to control the frequency and waveform of the AD9833. In this case, the value used to set the frequency must be split into two 8 bit values for the registers of the AD9833 since the frequency value is 16 bits long. The waveform is controlled using a separate register. The waveform register can be set to 0x28 for a square wave, 0x02 for a triangle wave, and 0x00 for a sine wave. Variables containing this information are also updated for use by other functions in the code.

Controlling the reference impedance: When the micro-controller receives a message to adjust the reference impedance, it first finds the desired impedance value from the 4th byte of the message and then depending on this value (1 for 1M, 2 for 100k, ... , 6 for 10) it sets the correct reference impedance.

Setting the reference impedance is done by making the correct relay connection before disconnecting the others (make before break) in order to always maintain a feedback resistance on the auto balancing bridge and prevent saturation/oscillation issues.

Once this is done, a variable containing the current reference impedance is set so that other areas of the code know what the reference impedance is set to.

Measuring the impedance: When the micro-controller receives a message asking for a measurement, it first accesses the output of the ADC. This ADC has a frequency of 2MHz and uses two channels, one for the magnitude of the reference signal and the other for the magnitude of the signal through the device under test. The ADCs output is constantly dumped directly into a buffer using direct memory access. When an ADC value is needed, the mean value of the buffer containing values for the DUT signal output is calculated and returned as the magnitude.

In order to calculate the phase, the micro-controller utilises interrupt timers to measure the phase difference between the reference signal and the signal through the device under test. This is done using 32 bit interrupt timers that are connected to the zero crossing circuitry. The timers each have two channels. When the first channel is activated on the rising edge of the reference signal the timer is set to zero, and when the second channel is activated the value of the timer is stored to a variable.

These are then combined into a single message along with the reference voltage signal magnitude (calculated in the same way as the DUT signal magnitude) and the current reference resistance as explained in a previous section.

7.2 Automatic Ranging Mode

During preliminary testing an initial auto ranging algorithm was developed.

When set to automatic ranging, the micro-controller switches the reference impedance to 1M (the highest value) and measures the average ADC value. If the mean value is at the maximum value of 4096 (thus the Waveform is clipping), the appropriate relay is set for switching to the next lowest reference impedance. This step is repeated until the measured ADC values are less than the maximum value.

While testing this algorithm it was found to be unreliable. Therefore another algorithm was designed which would compare the measured average value of the DUT voltage and current waveforms for each reference impedance, then choose the reference impedance at which the current and voltage values were the closest, and thus the reference impedance that was closest matched to the DUT. Unfortunately this was not implemented in time to be evaluated.

7.3 Calibration

In order to improve the accuracy of the measurements made, first of all the exact values of the reference impedance should be measured to be used in the calculation of DUT magnitude, instead of the nominal value, thus removing any inaccuracy due to tolerances. Where offsets were experienced in the circuit these should first be nulled as much as possible using the potentiometers on the board, and then after this be characterised and corrected for in software. During initial testing the manual nulling using potentiometers was the only calibration performed.

7.4 Companion Application Use

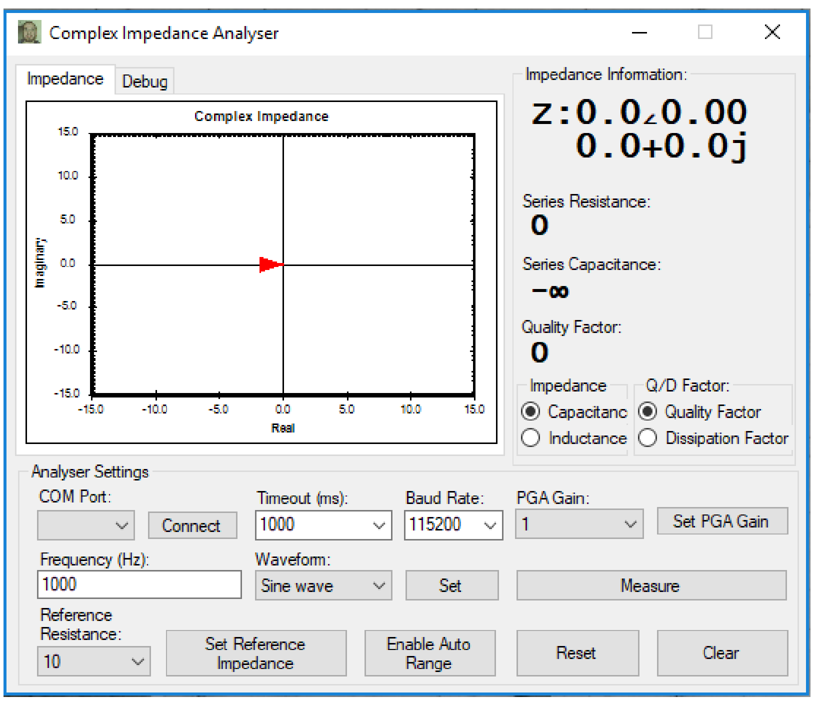


Figure 9: Companion application.

The application has several features that allow for easy measurement of the DUT.

- **COM port selection:** The application allows for easy switching of COM ports without the use of external software.

- **Baud rate selection:** Various Baud rates can be chosen without having to use other software.
- **PGA gain selection:** The excitation signal level can be varied by the user in order to replicate the signal levels the DUT would see in use. This is easily controlled using the PGA gain drop-down on the application.
- **Frequency and waveform selection:** This text box and drop-down gives the option to specify the frequency of the excitation as well as the shape of the waveform (sine, square, and triangle). If the chosen frequency is invalid then a warning message is displayed and the frequency message won't be sent.
- **Reference impedance selection:** This drop down gives the user the ability to set the reference impedance manually. Next to this is a control for switching into automatic mode.
- **Equivalent Series Impedance and Q/D factor radio buttons:** These controls allow you to display the equivalent series inductance or capacitance as well as either the quality factor or dissipation factor.
- **Measure, Clear, and Reset buttons:** These buttons send a measure message to the micro-controller, clear the debug screen, and reset the chosen parameters to default.

The impedance results are displayed on both an Argand diagram as a vector, and a complex impedance in the form $a + bj$ on the side.

The user interface also allows the user to choose resolving the measurement into parallel/series capacitance/inductance, instead of the impedance value. It was also planned to automatically resolve the impedance into a capacitance/inductance depending on the value of the measured impedance. This could have been performed by simply setting phase angle thresholds for which an inductor/capacitor is chosen. Alternatively this could have also been done by changing the measurement frequency very slightly above and below the nominal value and observing the change in the imaginary component of impedance. This method may have proved more reliable for lossy inductors and other similar DUTs as their phase could be close to the threshold if the method previously described was used, thus causing them to be resolved as the wrong component.

In the event that there are errors, the application can be easily debugged using the debugging tab of the application that prints the messages received and transmitted by the application in a human readable form.

7.5 GitHub Repository

All the code for both the micro-controller as well as the companion desktop application is available to view in a GitHub repository at `https://github.com/joshjennings98/instrumentation`.

8 Group Member Roles and Contributions

8.1 Jack Waller

- Concept Generation
- Schematic and PCB Design
- Prototype Assembly
- Testing and Evaluation
- Report Writing

8.2 Josh Jennings

- Embedded Software Development
- Companion Application Development
- Testing and Evaluation
- Report Writing