Vacuum Tank Data Acquisition System

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This report details the design processes and steps taken to develop a data acquisition system for use in a vacuum tank environment. This project served in part as a proof of concept for the development of a low cost, high volume data acquisition system, and also a functional device for use in the UNSW@ADFA vacuum tank. The project requirements are outlined and the engineering process undertaken in order to meet them is highlighted. The system is also characterised from a power consumption and error rate perspective with the results indicating that the final prototype has effectively managed to deliver a low power, low error system with sufficient software support for ease of use.

Nomenclature

DAQ	Data Acquisition
ADC	Analogue to Digital Converter
AtMega	AtMega328p Microprocessor
SPI	Serial Peripheral Interface
CS	SPI Chip Select
SS	SPI Slave Select (interchangeable with CS)
CPP	C++ Programing Language
IDE	Integrated Development Environment
LSB	Least Significant Bit
NTC	Negative Temperature Coefficient

I. Introduction

Data Acquisition (DAQ) systems are an essential element in the experimental process providing the means to capture and record data from the experimental environment. DAQ systems can take many forms but in general they operate by the use of some form of transducer to generate an analogue signal to which the system must them read and process [1]. The use of some form of digital system in the processing and storing stage, often leads to the requirement for the system to have an analogue to digital converter (ADC) of some kind. The type of ADC used is governed by the project requirements, specifically accuracy, sampling frequency and number of channels. Additional requirements on the system may also influence the types of hardware used. This paper concerns the design process and testing undertaken in an effort to generate a DAQ system for use in the UNSW@ADFA vacuum tank. The requirements of the system and the process taken to develop a solution will be examined. In addition, the system will be characterised in terms of performance and overall achievement of the project aims.

II. Project Requirements

The identification of project requirements plays a key role in the engineering process. The project requirements must be clearly defined so that the design processes undertaken will deliver an acceptable, if not optimal, solution. The project requirements will govern the engineering decisions made in the design process and ultimately determine the product to be delivered. The requirements of this project were heavily influ-

enced by the type of environment that this device will operate. The project requirements were to deliver a DAQ system:

1. Capable of operating in a vacuum environment;
2. Capable of reading between 32 and 128 analogue channels;
3. That causes minimal disturbance to the test environment;
4. That has the capability to transmit data wirelessly from inside the vacuum tank;
5. That has scope for further expansion to include actuator control, heater element control and a thermocouple interface.

These broad project requirements were then broken down into a more functional set of requirements to govern the selection of hardware and components.

II.A. Project Requirement 1 - Capable of Operating in a Vacuum Environment

The ability of the system to operate in the vacuum environment was explored and discussed from the perspective of the selection of hardware and components that had the capability to operate in very low pressures. Certain materials have the potential to degrade in a vacuum due to the phenomena of outgassing [2]. Outgassing occurs when gas that is previously dissolved in a material is released. This can cause physical changes in a material that may effect its ability to perform its desired task [2]. Without an exhaustive list of all materials used in each component, it was difficult to predict the level to which outgassing may become an issue. Early discussion on this matter concluded that the best and most time economical solution would be to continue with the development of the device and test it in a vacuum when available.

II.B. Project Requirement 2 - Capable of Reading from 32 to 128 Analogue Channels

This requirement clearly defines some of the hardware requirements of the system. The system must have analogue to digital converter (ADC) circuitry capable of converting up to 128 individual signals. In addition, it is desirable that the system has a minimum resolution of 10 bits and provide high accuracy results.

II.C. Project Requirement 3 - Causes Minimal Disturbance to the Test Environment

This project requirement had a significant implication to the system design. To clarify an adverse effect on the testing environment, the vacuum tank is designed to operate at both low pressure and low temperature. The purpose of the tank is to simulate conditions in space so that various test can be run and measurements taken. For the system to not adversely effect the environment, the heat generated by the system should be minimised so that the test environment was not overly disturbed. This project requirement therefore lead to a further requirement on the hardware and components, that they generate low amounts of heat. This was quantitatively evaluated by ensuring that the power consumed by the components was minimal, leading to minimal heat generation.

II.D. Project Requirement 4 - Has the Capability to Transmit Data Wirelessly from Inside the Vacuum Tank

This requirement refers to the need to be able to transmit data from inside the vacuum tank, to an external location for storage and processing. The selection of the wireless hardware was driven by the ability of the transmitting device to effectively operate at the range required and the tank environment.

II.E. Project Requirement 5 - Has Scope for Further Expansion to Include Actuator Control, Heater Element Control and a Thermocouple Interface.

There was scope in this project for future development of additional functionality. Some of these possible future functions included control over a heater element, control over a system of actuators and interfacing the analog channels with thermocouple amplifiers. While some of these functions fell outside the scope of this project, it was important to undertake the design process with these possible future functions in mind.

III. System Revisions

Certain project requirements placed some restrictions on the final device that must be met for it to be considered a viable solution. It was identified towards the middle of the project that the restriction on heat generated had the potential to be a significantly more important factor than first considered. For this reason the initial version of the device was reviewed and some of the major hardware components replaced.

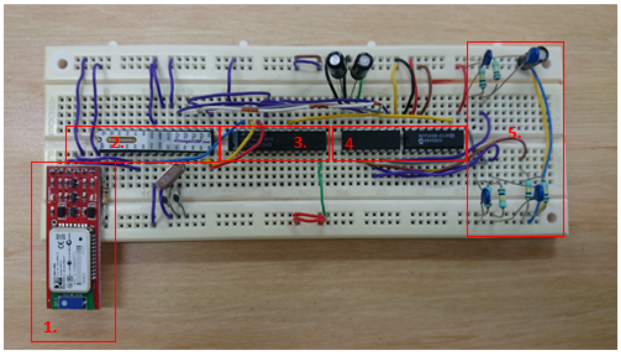
III.A. Version 1 - Raspberry Pi Based System

The initial internal processing platform was designed on a Raspberry Pi model A microcomputer with a WIFI wireless protocol employed. This system was initially chosen for its flexibility in programming languages, support to learn the system basics and an ease of availability. The system was an effective platform for interfacing with the required devices and a working prototype, capable of measuring temperature data was delivered at the halfway mark of the project. Through further tested in relation to its power consumed and thermal generation and it was concluded that it simply generated too much heat and would become a greater issue in future vacuum tests. This lead to a revision of the system as a whole and the development of a new system based around a different internal processing unit.

III.B. Version 2 - AtMega328P Micro controller Based System

The re-design of the system to operate using the AtMega328P micro controller was due to the comparatively low power consumption of these devices [3]. In addition it was desired that in changing hardware platforms, the functionality of the system was not lost. In addition to the replacement of the WIFI wireless device used in version 1, version 2 adopted a Bluetooth modem as the method of wireless communications. This was chosen as the result of a feasibility analysis undertaken on Bluetooth in the vacuum tank to determine if it could meet the required needs of the system and the reduced power consumption of Bluetooth compared to WIFI [4]. The major implication to the work required in the shift from version 1 to version 2 was found to be in the re writing of the software to support the internal hardware. The nature of the micro controller required that the software be re-written from python into C++. This was a significant time cost that impeded the progress of some elements of the project. The second revision interfaces with the same ADC used in version 1, the MCP3208 and MCP3008. These devices were chosen for their low power consumption and high availability. The micro controller interfaces with the ADC chips using Serial Peripheral Interface (SPI) a method of digital communications. To enable the selection of a large number ADC chips, a 74HC154 multiplexer/demultiplexer was used to expand the chip select (CS) line using 4 digital output pins from the micro controller. The CS line is used to select the desired ADC chip for the SPI to communicate with. This device was again chosen due to its low power consumption and wide available.

The following figure shows the prototype of version 2, mounted on a breadboard with each of the major components detailed.



1.	Bluetooth Adapter
2.	AtMega328P
3.	74HC154 Multiplexer/Demultiplexer
4.	MCP3208/MCP3008
5.	Test NTC Thermistors

Figure 1. Version 2 Prototype With Major Components Noted

IV. Power Analysis

The following results were obtained as a method to characterise version 2 of the system from the perspective of power consumption. In order to gather these results, a 1Ω shunt resistor and oscilloscope was used to establish the power drawn by the circuit [5]. This method was used so that the power could be found in real time and compared with the executing code on the system. This gave an excellent insight into the power consumption of the system in a range of states.

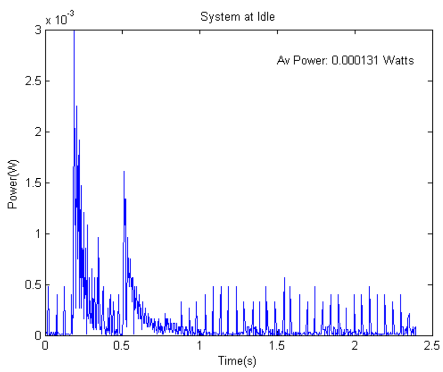


Figure 2. Power Consumption - System at Idle

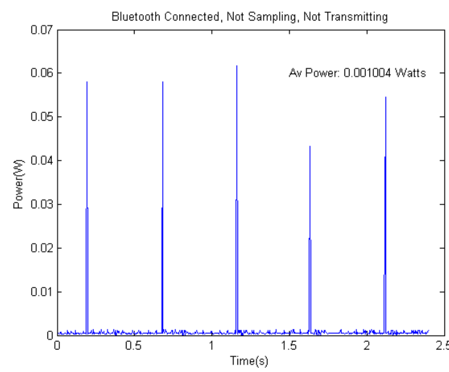


Figure 3. Power Consumption - System at Idle with Bluetooth Connected

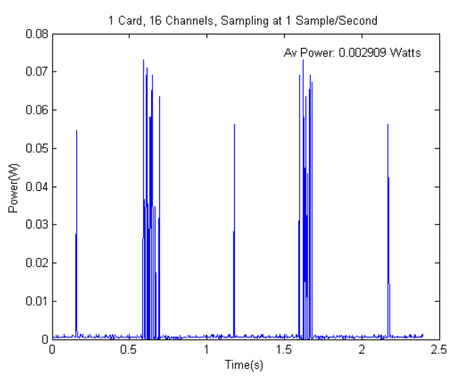


Figure 4. Power Consumption - System Running

Examining the plots above first to last, we can observe that when the system is at idle, neither sampling or transmitting, the average power consumed is very low. This period would be indicative of a the system prior to the external computer making a connection to the internal system. The next plot indicates the power consumed with the Bluetooth connected but the system not sampling or transmitting data. This situation

would be observed when the system has made a connection with the external computer and is either waiting for a command to be received to begin sampling. Or this could indicate the period in between samples where the system is in an idle state over before the next sampling period. The final plot indicates the system during operation, sampling at a rate of 1 sample per second across 16 channels. The period in which the system is sampling and transmitting is clearly visible as the more active power areas on the plot. Of note, the average power consumed is still considerably low at a value of 2.909mW.

Note that this plot does not indicate the system operating at the full 128 channel capacity. This is due to the current limitation on the system having only two ADC chips running. In order to have a functioning system without the need for the full 16 ADC chips, the system has been designed to operate on a card system where a card contains two ADCs and the system can operate from 1 to 8 cards where required. The purposes of this configuration is twofold, it allowed the development of the system to be undertaken without the need to purchase all the required components for the full 8 cards before testing. In addition, during real operation it is anticipated that many tests will not require a full 128 channels, as such additional cards can be removed to reduce the operating power and heat generation.

To characterise the system at full capacity and ensure it meets the low power requirements of the project, the obtained data, and the quoted maximum values were combined to ensure that, at worst case, the device would still draw significantly less power than the previous version. Using the quoted worst case values given in the manufacturer data sheets [6] [7] it was established that the system had the potential to draw an average power approximately equal to 2.994 mW at worst case. This value can be compared to the Raspberry Pi that had a measured average power consumption at idle with no connected peripherals of 0.75W. As this shows, the system has achieved a significant reduction in power.

V. Error Analysis

An important element of any digital data acquisition system is the accuracy of the measurements taken. At face value, the bit resolution of the ADC chips taken govern the absolute maximum level of accuracy obtainable by the system. For a 12 bit ADC such as the MCP3208, this gives a total number of quantisation levels of $2^{12} = 4096$. This means that the reference voltage supplied to the ADC chip, in this case 5.06V, is divided into levels based off the bit resolution. The maximum sensitivity governed by the bit resolution is therefore $5.06/4096 \approx 1.234$mV. This would correspond to whatever sensor is used based on the specification of that sensor. The true error rate of the system, however is likely to be greater than the quantisation error in the system. The MCP3208 [7] and MCP3008 [6] have a quoted error of $\pm$ 1 least significant bit (LSB). This means that using these devices, an error of 1 quantisation level above or below the actual value can be expected.

In order to quantify the error in this system, a series of measurements were taken for a constant input voltage taken from the ADC reference voltage itself. To get a full measure of the error, the reference voltage was reduced by a factor to allow measurement both above and below the reference voltage without clipping. The following figures illustrate the obtained results for the version 2 system operating outside the vacuum.

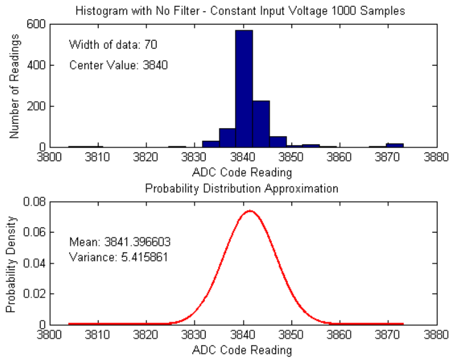


Figure 5. System Error - No Filter

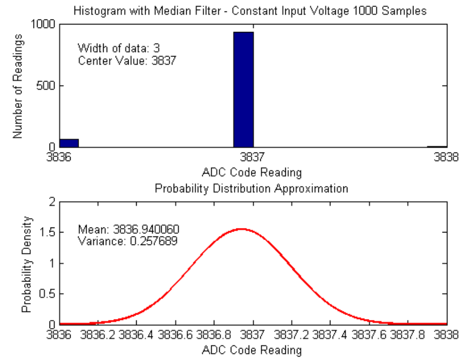


Figure 6. System Error - Median Filter

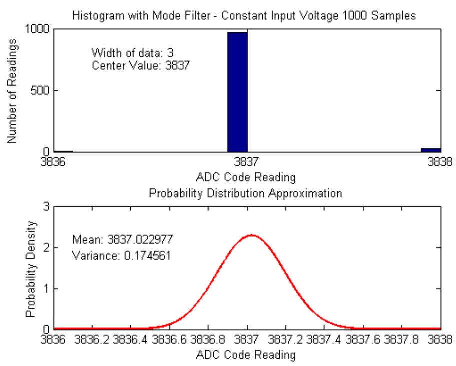


Figure 7. System Error - Mode Filter

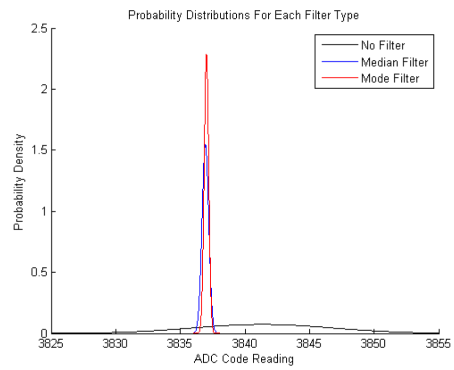


Figure 8. System Error - Probability Distribution

Figure 5 shows the error in the system with no digital filtering employed, in the form of a histogram. This type of plot demonstrates the number of occurrences that a certain data value is obtained. As the figure shows, the values measured fall within a large spread of data with a total width of 70. This is a significantly worse error rate than the ± 1 LSB quoted previously, which lead to the implementation of different filtering techniques. The most likely source of system noise is minor variations in the reference voltage supplied to the ADC. To mitigate this, analogue filtering could be employed to reduce the ripple in the reference voltage. Alternatively, digital filtering can be employed to process the data in such a way that the effects of the ripple are removed. Noting the normilised distribution of the data obtained in figure 4, it was anticipated that the implementation of a median or mode filter would be an effective method for reducing the system noise. A median filter works by oversampling the signal so that multiple values over the required period are taken. These values are then sorted and the median value taken as the true point. Mode filtering is similar but after sorting the data, a percentage of the middle samples are taken and averaged. Both of these methods were implemented and the data was plotted on a histogram for comparison. As figure 6 and 7 show, the implementation of both filtering techniques have restored a ± 1 LSB error margin. For a quantitative assessment of the performance of the filters, a comparison of the probability distribution of each filter was given in figure 8. To interpret the probability distribution, the narrower the waveform, and higher the peak indicates a reduced overall variance. For our purposes, this demonstrates a lower error. As the plot shows, the mode filter out performed the median filter by a significant margin.

Another important element to quantifying the system was to obtain measurements for the system error in the vacuum environment. This was done using a smaller vacuum oven as the vacuum tank was not available for use at this point. Initially, the constant voltage was supplied to the test channel using a 1N4004 diode to induce a constant voltage drop for the purpose of measuring error. The following figures demonstrates the initial error results obtained with a mode filter during pump down of the oven and at a minimum pressure of 6 Torr.

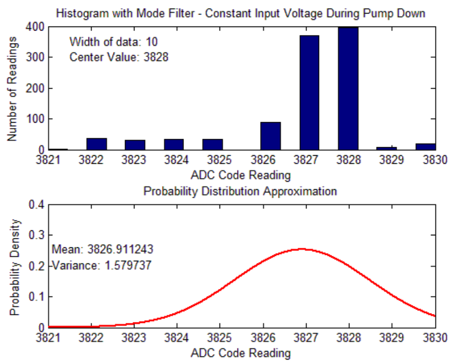


Figure 9. System Error - Vacuum Oven Pump Down

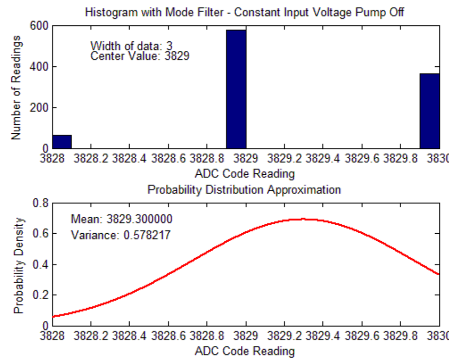


Figure 10. System Error - Vacuum Oven 6 Torr

This data was initially a point of confusion as there has seemingly been an increase to the error rate during pump down. Further investigation demonstrated that this error rate was not an accurate reflection of the error in the system. To further analyse the environment inside the vacuum oven, the temperature of the vacuum over was monitored using a thermocouple positioned inside the tank. The results of this test provided some clarity into why this additional error was being observed.

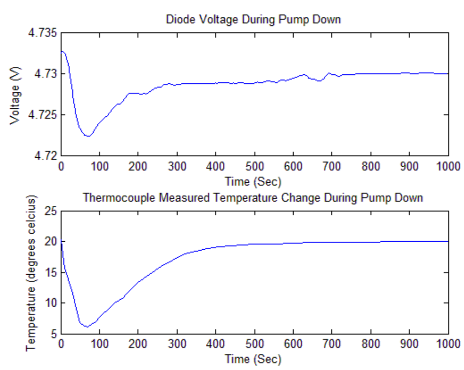


Figure 11. Comparison of Measured Constant Voltage and Temperature in Vacuum Oven

Figure 11 shows the measured voltage at the diode and the thermocouple temperature measurement. As the results show, during the pump down of the vacuum oven, there is a steep decrease in temperature before it slowly returned to approximately room temperature. Comparing this to the voltage at the diode, we can see that as the temperature decreases, the voltage drop across the diode increases resulting in a lower measured value at the ADC. This is due to the quoted constant voltage across the diode only being rated at one temperature. This therefore accounts for the perceived error in the system, and ironically demonstrates the sensitivity of the system to these minor changes in voltage. To better characterise the system without the effects of the diode, the tests were repeated using a simple voltage divider circuit. This circuit induces a voltage drop using two resistors to approximately halve the reference voltage prior to measuring.

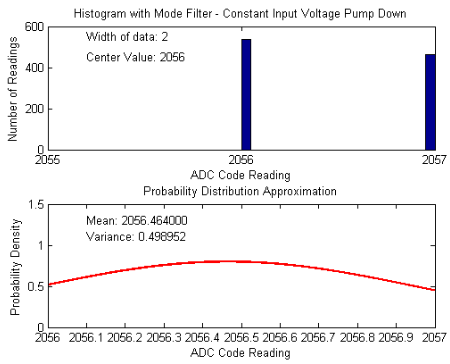


Figure 12. System Error - Vacuum Oven Pump Down (Voltage Divider)

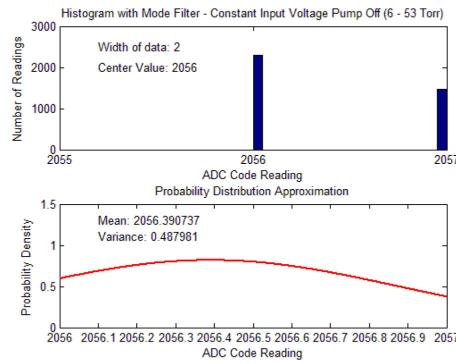


Figure 13. System Error - Vacuum Oven 6 Torr (Voltage Divider)

As these results demonstrate, the error rate has returned down to the maximum accuracy of ± 1 LSB during both pump down and at minimum pressure. This suggests a reliable level of accuracy despite the effects of temperature and pressure changes.

VI. Practical Application

Whilst the primary aim of my project is to deliver a system capable of acquiring data from a range of sensors but not necessary deliver the sensors to be used, it was decided that the system should be practically tested with a similar sensor to what may be used. As such, the system was configured with 4 negative temperature coefficient (NTC) thermistors. The thermistors used were not highly accurate or response, but the primary aim of this task was not centered on the sensors themselves, more to give an indication of the systems ability to operate as it will be required to in the future. The thermistors had a thermal response time constant of 16 seconds and an accuracy of 1 percent. The time constant of 16 seconds means that the rate at which the device can change its resistance to match a temperature change is a 16 seconds to change by 63.2 percent [8]. This response time is much slower than a thermocouple and as such we would expect to see the thermistor react much slower than the thermocouple.

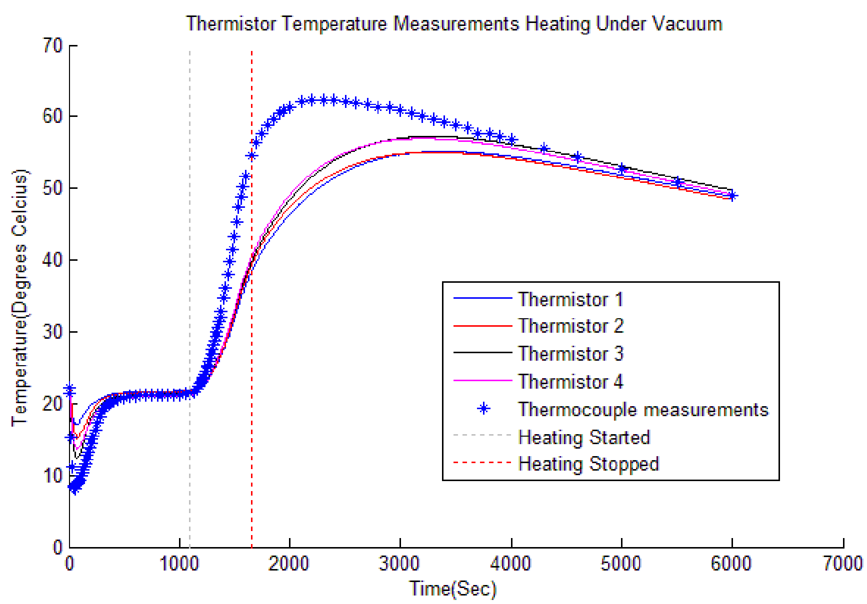


Figure 14. Practical Application - Thermistors Heated in Vacuum

As figure 14 demonstrates, the system was capable of gathering and storing the thermistor data effectively.

The figure demonstrates the reduced responsiveness of the system and the inaccuracy present in the thermistors themselves. The normal method for calculating temperature from the thermistor resistance is to use the Steinhart–Hart equation [9]. This equation requires that certain calibration tasks be undertaken on each thermistor to reduce error. As this was simply a functional test, the specific calibration tasks were not undertaken and instead a the simplified beta equation was used to approximate the temperature. This will account for some of the error present in the plot shown. In addition, the time constant of these thermistors demonstrates a significant error between the thermocouple and the thermistor data. Without appropriate calibration and measurement this data will contain numerous unknown effects occurring withing the tank. The thermocouple data presented was from a thermocouple measuring temperature external to the DAQ system. This was used as a point of reference to compare the received results. The image effectively demonstrates a situation where thermistors are used by the system to measure temperature data. This, however, is not designed to be indicative of the actual measurements that the system would make. It is likely that the actual measurements would use a better quality, more accurate temperature sensor.

VII. Software Support

With the decision to replace the internal hardware with an AtMega microprocessor, it was necessary to reprogram the internal hardware with C++. This posed a significant time cost on the project as the original system was designed to operate using Python based code, a much higher level programming language. Whilst the internal code was not used in the final version, the external GUI and processing code was re-purposed for use with this system.

The internal software is designed to sit in one of two states. The "idle" state is actually the system waiting to receive its command parameters from the Bluetooth adapter. Once these parameters are received the system throws a flag to indicate that it is ready to sample and moves into the data acquisition state. This state lasts for the period defined by the command parameters or until the Bluetooth adapter receives the abort command from the external computer. In this state, the system aquires data from the slave devices (ADCs) using the Serial Peripherals Interface (SPI) method. This data is sent as a ADC code via the Bluetooth adapter back to the external computer. The data is not processed on the internal hardware to reduce overheads and power consumption. On completion of the time given by the command parameter, the system resets its flag and moves back into a state waiting for new command parameters.

In addition to these two states, the system has a delay function that was re designed to allow some functionality to be maintained as the system waits. The standard delay function sets the system to a state of idle for the defined period. This posed an issue as a delay was desired between required samples but a level of control needed to be maintained to allow an abort parameter to be registered and acted upon. To fill this need the conventional delay was replaced with a re-written loop based delay that allowed the Bluetooth buffer to be checked for an abort command.

The external computer software is written in python and delivers a simple GUI to modify test parameters, execute and abort the test. In addition the external computer stores the data in a comma separated variable (CSV) file for ease of processing in MATLAB, Excel or other common tools. The external program takes advantage of threading to allow the simultaneous collection and storage of data whilst maintaining control over the program. The external software was also used to implement user restrictions on the sampling time based on the parameters selected. Due to the requirement for the internal hardware to undertake a number of processes between samples, there is a minimum sample time that the system cannot operate below. This time is dependent on the number of active channels and the selected filtering to be applied.

VIII. Future Work and Recommendations

The system has been delivered as a working prototype to a system that would fit the project requirements and deliver the required functionality of wireless data acquisition. There are however additional features and tasks that could further enhance or make the project a better long term solution. There were elements of this project that had to be scoped out of the final delivered item due to time constraints. The following recommendations for future work would serve as a good guide to the total completion of the project.

VIII.A. PCB Design and Mounting

To improve the usability and robustness of the hardware, the system should be mounted on an appropriate PCB. This would remove some of the negative effects that breadboard mounting can entail such as the high capacitive nature of the breadboard and simple propensity of loose connections occurring.

VIII.B. Extensive Software Testing

The software was used throughout all the tests to receive results for this report. This provided a reasonable level of testing for the software, however a more rigorous testing of the software would likely reveal some additional flaws or at a minimum reveal some areas that could be optimised.

VIII.C. Higher Precision Sensor Testing

The sensors used to test the device in a practical application were not of a sufficient level of accuracy to truly reflect the type of sensor that maybe employed for actual use in the system. Re-assessing the system using a more precise sensor would be a valuable exercise to determine its true performance in this area.

VIII.D. Test in Main Vacuum Tank

Unfortunately, due to the unavailability of the vacuum tank for testing in the later stages of the project, the system was not tested in the main vacuum tank. I believe that it would be a beneficial exercise to test the system in the larger vacuum tank to test the effects that this may have on the system.

VIII.E. Processing and Reviewing Software

A useful inclusion to the project that eventually fell outside the time frame for delivery was an addition to the external software suite to allow the user to specify sensor profiles and automatically process the data. Additionally, an added feature for the user to monitor sensor levels as the system is sampling would be a useful feature.

IX. Conclusion

This project has provided important results that have allowed some useful conclusions to be made in relation to the viability of using this hardware as a replacement for a commercial solution. This hardware has been delivered on a low budget, using components that meet the requirements but are also cheap and widely available. These results have demonstrated that this system is a viable option to allow the sampling of a large number of sensors in the 1kHz range. In addition, these results have looked at the accuracy that can be achieved by this device and conclude that the maximum accuracy of the ADC devices, with the addition of digital filtering, can be achieved. This accuracy consists of ± 1 LSB for these ADC devices, equating to an accuracy of 0.0037V out of a total 5.06V this equated to a error of 0.0732 percent. Obviously this accuracy will be dependent on the maximum accuracy of the sensor used.
The results obtained have demonstrated that the project aims have been met and a viable solution developed to provide the capability of wireless data acquisition of 128 channels at a high level of accuracy.

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