Harris Cold Plate Testing Rig

Patrick Armengol, Adam Blair,
Eric Guest, Jinjin Lin
Dept. of Electrical and Computer Engineering, University of Central Florida, Orlando, Florida, 32816-2450

***Abstract* — Harris corporation is experiencing some unknown phenomenon in the heat characteristics in some of their projects when a pulsating flow of air is introduced over a cold plate (heat sink) under normal operating conditions. This project aims to supply Harris with a platform to test different flow conditions over cold plates and enables them to obtain relevant data so that they can better study this phenomenon.**

I. Introduction

The Harris Corporation is experiencing some unexpected phenomenon in the flow characteristics of a few of their projects. This phenomenon was initially observed when a pulsating air flow moved across a cold plate under normal operating conditions while heat was being dissipated by the plate. The goal of our project is to create a cold plate testing apparatus that can be used to simulate the conditions needed to observe said anomaly and obtain detailed data about the flow characteristics and heat measurements under both a steady state (airflow at constant velocity) and pulsating (airflow in a sinusoidal velocity profile) case. This project was accomplished by us, ECE Senior Design Group D/18 in collaboration with an MAE Senior Design team along with consultation from a head flow expert at UCF. This project spanned the Spring and Fall semesters of 2015 and was fully funded by Harris through a $10,000 grant given to UCF for the purpose of this project.

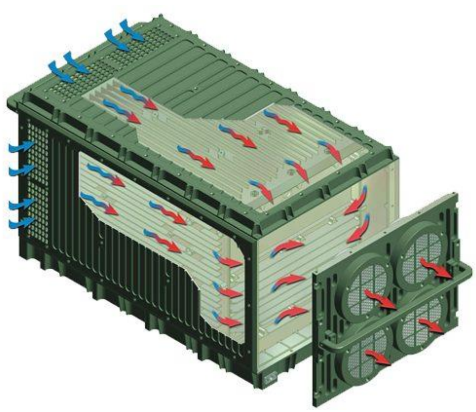

Figure 1 - Typical heat exchanger used by Harris

II. Design Overview

The design of the test rig consists of a few distinct parts, the fan, the duct, the heaters, the sensors, and the power supply. The air is sucked through the rig by a fan placed in a pull configuration at the end of the box. This was done to prevent any potential turbulence typically generated by a push configuration. The specific fan we used was chosen because of its ability to ramp up and down (necessary to create the sinusoid airflow we require) at the fastest rate possible while maintaining the airflow we need for the maximum output case. The fan is modulated by a fan control system which is explained in detail in section III.

The airflow created by the fan and controller system passes through the duct which consists of cold plates which are just a thin aluminum plates located on the top and bottom of the duct. The plates are heated by an array of heaters located directly outside of the plates. The thickness and material of the plates and output of the heaters were chosen based off of very specific heat requirements calculated by the MAE team.

We were required to take key measurements within the system which will eventually be used by Harris to help determine the cause of their phenomenon. These measurements are temperature readings from multiple locations along the plates, a pressure differential measurement from the front to rear of the duct, air velocity, and mass flow measurements. These measurements can then be used to find the heat transfer coefficients of the heated duct.

The majority of power to the system is delivered by a DC power supply. The power supply we chose has multiple different rails capable of delivering the numerous voltages we require at a very high amperage. The power supply drives the fan control system which in turn powers the fan. A boost converter is also attached to the power supply in order to drive the heaters at variable voltages. Power system specifics are further detailed in section IV.

A large part of the construction of the test rig made by the mechanical team, however most of the electronics were handled by our team. Each of the components including have specific intended locations determined by the MAE team. Therefore it was imperative that we worked closely together to install each of the parts so that we can get relevant data that fits the model for exact calculations and a functional fan control.

Although the testing rig is substantially larger than the physical cold plates being tested, it still exhibits flow characteristics similar to a real environment application. The larger the physical size of the test bed, the easier it is to measure data from localized regions of the rig

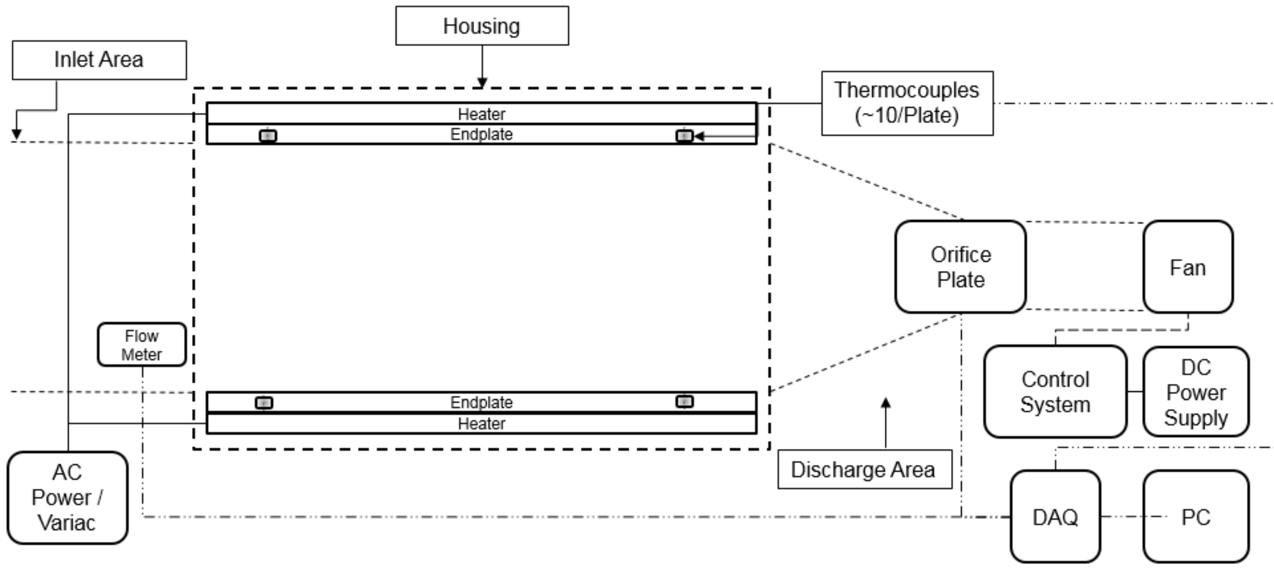

Figure 2 - Full system block diagram

III. FLOW CONTROL

The velocity of the air flowing through the testing rig can be configured to be a steady state flow or a pulsating flow. Harris specified that the velocity of the air must follow the following equation for the pulsating case.

$$V= \mathbf{A(1+Cos(2ft))} \qquad (1)$$

The variable A is set so that the Reynolds number for the air flow is at least 1000 and less than 10,000. For our particular duct, this was calculated to be at least 1.5 m/s. We decided to use a 120mm computer fan to generate the air flow because it has a good response time compared to other air flow generating devices such as compressors, vacuums, and centrifugal air blowers. The fan is controlled by applying a voltage across it and the speed of the fan is proportional to the voltage applied to it. We initially thought that we would need to create a feedback control system to create a distortion free cosine wave but when we tested our device we found that at our frequency range as long as the fan is able to draw as much current as it likes the resulting air velocity profile is perfectly sinusoidal. This was great for us because it simplified our design significantly. To generate the function above, we created an analog controller, as seen in figure 3.

The function generator is designed to produce an air velocity in the duct that follows function 1. The output waveform is built in two stages. First a sine wave is generated using a wien bridge oscillator. The amplitude of the sine wave is attenuated and summed with a DC offset using a summing amplifier. Secondly the output power is amplified so that matches the velocity range we are looking for. Finally the the function is passed through a voltage follower to drive the fan. This last stage is important because the circuitry that generates the function cannot drive a large load. To implement a voltage follower we decided to use a FET transistor because it can easily be controlled with an op amp and is capable of handling a large current. One downside to this approach is that it generates a lot of waste heat in the transistor which then needs to be dissipated with a heat sink so that the FET does not burn out.

We decided to use an orifice plate in our design because it has a faster response time relative to other mass flow sensors for its price. The orifice plate works by obstructing the duct and forcing all the air through a small hole in the center. When the air is forced through the hole it creates an area of high pressure upstream of the hole and an area of low pressure downstream of the hole. A differential pressure sensor can be used to measure the difference in pressure between these two regions. While the orifice plate is relatively cost effective, accurate, and has quick response time, it has a few disadvantages. One of the main disadvantages of the orifice plate is it requires a laminar flow and to achieve this flow there must be a region of straight, symmetrical uninterrupted duct. Measuring a region that is length 4 diameters upstream and 4 diameters downstream. Another disadvantage of the orifice plate is that it has it does not function very well at pulsating airflow at high frequencies. We were lucky that for our frequency range of pulsating airflow that the orifice plate was able to handle it quite well. This made the orifice plate the perfect option to incorporate of the build of our testing rig.

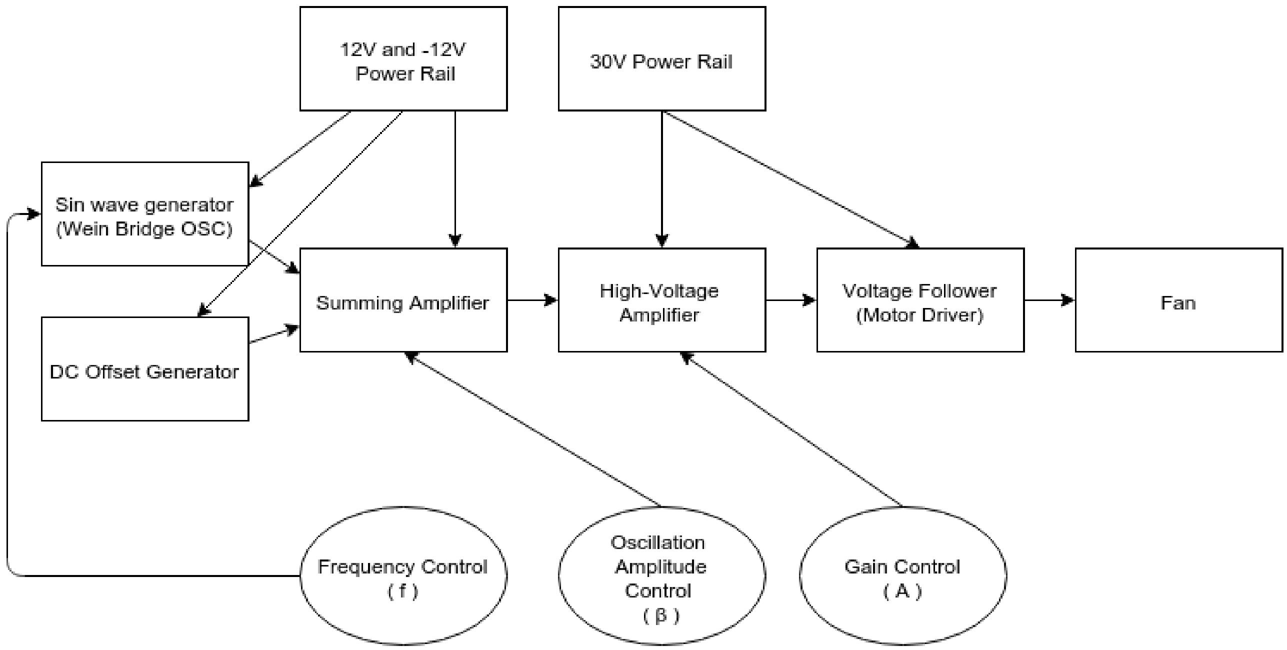

Figure 3 - Block diagram of the function generator

A major requirement of the project by our sponsor was that we needed to have an accurate air velocity measuring device with a response time of at least 4 Hz. We initially had decided on using an orifice plate because it has a reasonable response time and could measure both mass air flow and air velocity. We then switched to pitot tubes because we were not able to find an orifice plate that would fit our specifications and be able to reach us in time, though we ordered the orifice plate anyways with the hope it may arrive in time. The pitot tubes proved not to have the sensitivity necessary and they were then replaced with a rotameter and a hotwire sensor. We got both because the rotameter is effective at measuring steady state mass air flow but cannot measure the pulsating airflow in a way that would be useful to our air flow feedback control system and the hotwire sensor can measure air velocity with great accuracy and response time but can only be used to estimate mass air flow because it measure only one point in the duct. The rotameter created to much resistance in the duct and our fans could not handle the static pressure. We then tried to use a vacuum as our air flow producing device but while it could produce significant air flow and could overcome the static pressure it was difficult to control in a transient fashion. In the end we ended up having to configure the duct in two ways. One for the stead state case and one for the pulsating case.

For the steady state case we used a vacuum, hotwire sensor and rotameter to get mass air flow data. And in the pulsating case we use the fan and the hotwire sensor to get air velocity data. We use the hotwire sensor in both cases because we can correlate the velocity at one mass air flow measurement with the velocity measurement in the pulsating case to estimate mass air flow. While this is not completely accurate, it gets us something with what we had. The orifice plate may still arrive before the semester is done, we will have to wait and see.

IV. Heat Control And Power Delivery

The purpose of the heaters is to simulate a load such as hot electronics that may be housed inside of one of Harris' units. The heater is sandwiched between the insulating plate and the cold plate. This way the heat from the heater is forced to flow to the cold plate and the efficiency of the system is maximized. Our heater requirement was up to 120W per plate for a total output of 240W. We elected for flexible mat heaters because they could be easily sandwiched between the cold plate and the insulation plate and provided the required heat output at a reasonable price. Because these heaters are essentially large resistors we simply need to just adjust the voltage supplied to them in order to change their heat output. To measure the output of the heaters we set the input voltage to a set interval and measured the amperage draw, which when multiplied together gives us the total watts. We did this for multiple voltages in order to create a graph of input voltages and their corresponding heat outputs, as seen in Figure 4 below. Although we would have liked to have a very simple setup

Component	Voltage	Current	Amount in System
Fan	12V	3A	1
Thermocouple ADC	3.3V	400 uA	7
Pressure ADC	3.3V	4.8 mA	1
Fan Controller	12V and -12V	20 mA	1
Pressure Sensor	3.3V	2 mA	2

Table 1 – Power Requirements

of just two heaters, one for each plate, because our rig is so large we had to go with four heaters per plate for a total of eight heaters all together.

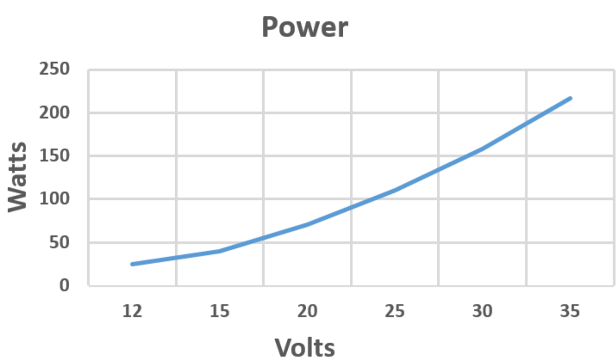

Figure 4- Voltage vs. power of the heaters

In order to supply voltage to the heaters, fans, and other electronics we went with a computer power supply. These power supplies are affordable, compact, have a very high output, and supply all of the different voltages we need. We had originally planned to use two separate power supplies, an AC variac for the heaters and a hand-built DC unit for the fan and electronics. We decided against the variac when, after some further calculations from the mechanical team, we realized our heater output was actually much less than we originally thought, now drawing a total of just 240W. This wattage is easily attainable by a standard computer power supply so we decided to consolidate to reduce complexity. Our original plan was to build the DC power supply ourselves by following schematics from Texas Instruments. We decided against this though when we realized the complexity, cost, and time it would require to create a high output, multi-rail system capable of delivering the multiple voltages and high amperage we needed. The minimum requirements of our power supply were that it must be able to output +12V @ 25A, -12V @ 0.5A, and +5V @ 0.5A and have an input of 120V AC @ 60Hz.

Our power supply outputs up to +12V but our heaters require much more voltage than that and the voltage needs to be adjustable. In order to achieve this we elected for a boost converter which has a 12V input and a digitally controlled variable output of 12-80V. The boost converters we chose have a maximum output of (input voltage * 10A) which in our case gives us 120W, just enough for one plate. So in order to get the plates hot enough for the maximum load case of 240W we hooked each boost converter up to half of the heaters. The converters are adjusted with simple button clicks while a real-time voltage output is displayed on the digital screen. The fan control system also required a modified voltage which required a separate, smaller boost converter. Because we elected to over-volt the fan in order to get it to ramp up quicker our control system needed a little more than the 12V supplied by the PSU. A small boost converter was added and tuned to give an output of 15V to the control system.

V. Sensor Interface

The purpose of using the temperature sensor is because the temperature measurement is most important objective of this project. It can be used to analyze how steady state airflow and pulsating air flow can affect the temperature inside of the test rig. Secondly, temperature data is required to calculate heat transfer coefficient for our project. There are many options of temperature sensors on the market. The reason we chose thermocouple was because it is relatively affordable, has a fast time constant, is fairly linear, stable, accurate, and can potentially have wide temperature range. Most importantly, no input power is needed for the device to function. Finally, we selected T type thermocouples, because they have high accuracy at low temperatures and are approximately linear over 0°C to 60°C. The thermocouple temperature measurements involve two important factors: measurement of the thermal gradient from the cold junction available from the thermocouple according to Seebeck effect and the actual temperature on the other end of junction measurement.

However, the output in terms of voltage of the thermocouple is too small, in the range of mV, so a low noise amplifier is required to boost up the output voltage of the thermocouple. Also, since the differential voltage output at the connector corresponds to the relative temperature from hot to cold junctions, the resultant value measured needs to add the a voltage representing the actual temperature at the cold junction to accurately measure the hot junction temperature. This process is known as cold-junction compensation and we employ it in our design.

Since the temperature varies in different locations of the test rig, a large amount of the temperature sensors are required to complete the task. However, the total number of temperature sensors is limited by the number of ports on our DAQ. We initially wanted 40-50 sensors but eventually settle on a total of 20 to reduce complexity and cost at the expense of overall accuracy. The sensors were distributed in different locations, 8 of them on the top of the plate, and rest of them in the bottom of the plate. Temperature readings are more important at the inlet (where the temperature gradient is still forming) than they are at the outlet where the temperature is relatively uniform. Because of this, the sensors are denser near the entrance than at the end in order to increase accuracy in that critical area.

VI. Data Acquisition

The last of the project's requirements is a system for acquiring sensor data. The customer specified a need for a way to collect appropriate and relevant data from sensors. This collection method needs to be accurate, customizable, and efficient. The gathered data should be easily manageable by those analyzing it.

Our projected sensor system includes numerous thermocouples for temperature measurement at a high physical resolution. It also includes a pressure sensor for precise air flow and velocity measurements. Our data acquisition (DAQ) system needs to be able to interface all of the sensors appropriately. The customer expressed a desire for a high resolution and throughput rate. There should also be at least ±1° C accuracy on the thermocouple measurements. The customer also requested that the system be able to be interfaced and modified comfortably by Harris engineers without electronics or programming experience. The rest of the design decisions were left to our own discretion.

We proposed two solutions for this system design. The first is a pre-built DAQ. This entails the purchase of already available, standardized DAQ units in the market. The other solution the design of a custom DAQ consisting of a custom PCB, hand-picked components, and a capable controller unit. A system block diagram for both solutions is shown in Figure 6.

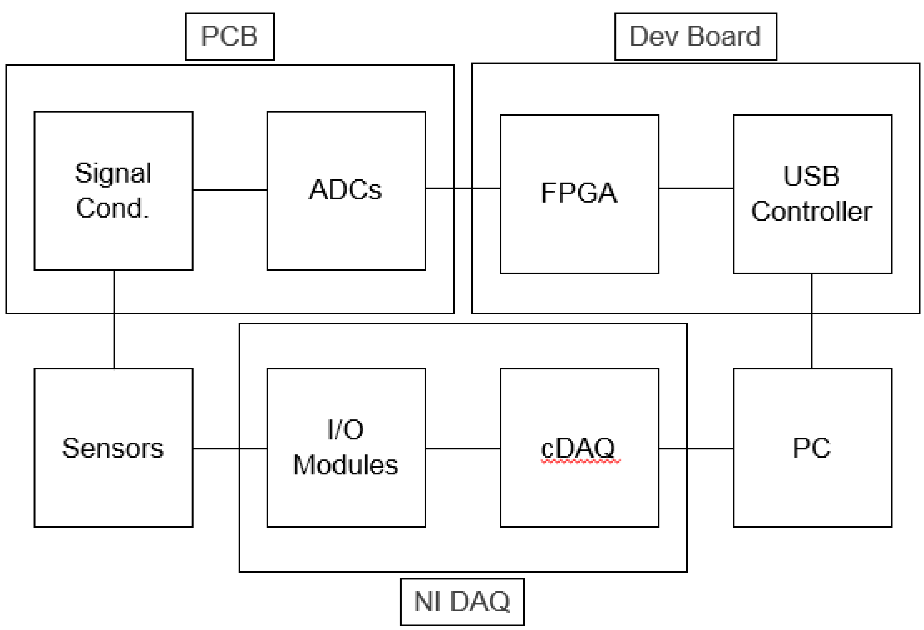

Figure 6 - DAQ System Block Diagram

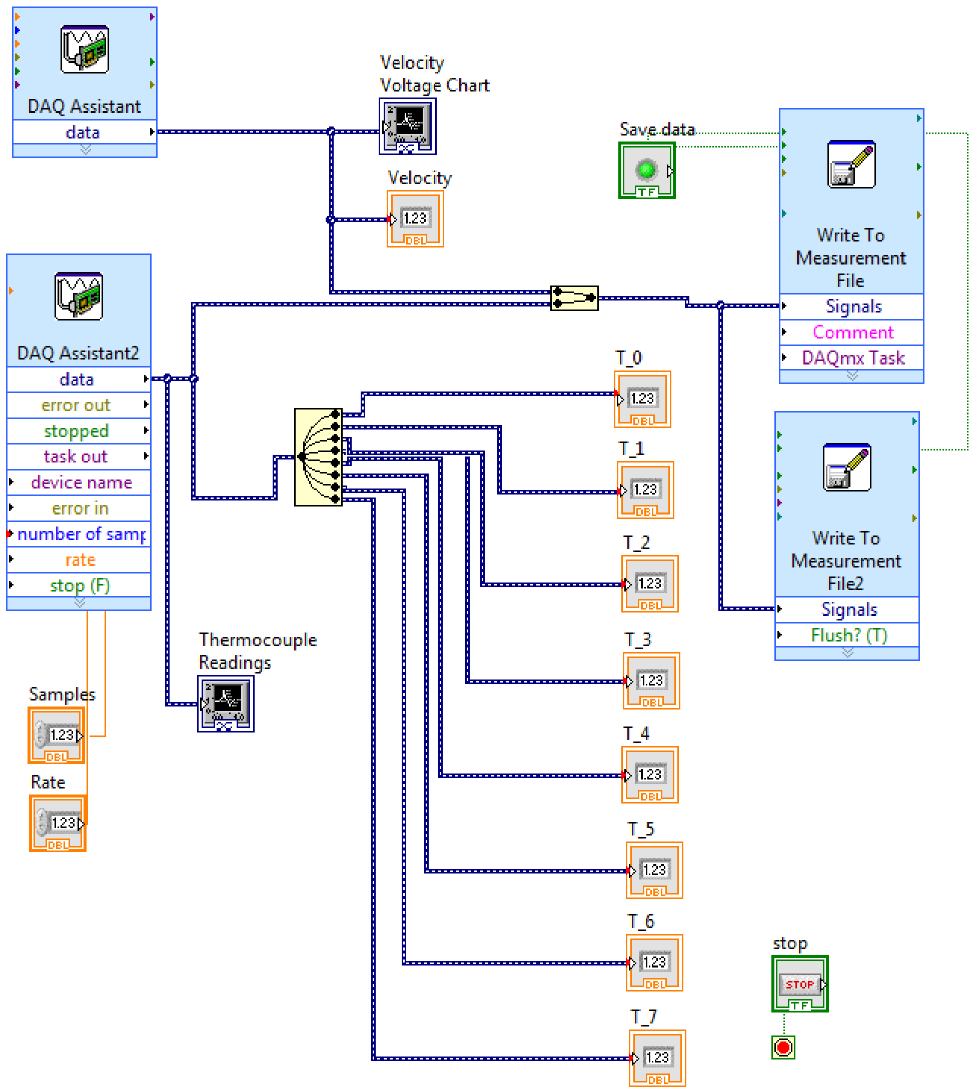

Figure 7 – Labview representation of our DAQ

A. Pre-built DAQ

This solution is the prime candidate for presentation to the customer. This is because it provides an already tested configuration that adheres to most of the customer's requirements and requests. It is sufficiently accurate, adequately expandable, and most importantly, (re)configuration of the system can be done with little difficulty. The major issues with the system mainly deal with low efficiency in areas like sampling rate, throughput rate, scale, and cost.

For our implementation, we decided to go with National Instruments (NI) products as they provided the most flexibility for different types of inputs and compatibility with tools like NI LabVIEW. The controller unit is a CompactDAQ that is meant to be used with accompanying sensor-based I/O modules. The modules we picked out are the 4-channel NI 9211 and 16-channel NI 9213 thermocouple modules which supply us with a total of 20 differential thermocouple inputs. To interface the flow meter, we have an NI USB 6000 DAQ. The controllers have a USB connection with the PC for reasonably fast standardized communication. The host program was drawn up in LabVIEW utilizing various useful DAQ Assistant features for collecting, converting, and storing the incoming data. The software also provides a nice customizable GUI for visualizing and monitoring the data as well as controlling certain sections of the system.

In its current configuration testing long term flow analysis, the DAQ system is interfacing 20 thermocouple sensors and 1 flow meter. It does so at a low rate of 5 samples/sec for each input, but it is capable of much faster rates. This test data is being saved, analyzed by the MAE team, and sent to Harris for review.

B. Custom DAQ

The custom DAQ design aims to provide solutions to the shortcomings of the pre-built DAQ. It is a proof of concept for a more flexible DAQ system that can conform to the requirements of any project involving sensor measurements. It is much less costly and is equipped to handle high data rates.

Much like the prebuilt option, our implementation consists of sensor interface units, a control unit, and a processing unit. We designed and built a custom PCB that houses the sensor connectors and signal conditioning/conversion units. The PCB is connected through external pins to a development board control unit.

On the PCB are 18 vertical surface mount thermocouple connectors from Omega and a 3 pin terminal block to connect the flow sensor. The thermocouple inputs go through signal conditioning circuits for type T thermocouples found in reference designs like [1]. The flow meter input also goes through a decoupling capacitor to stabilize the input. This conditioning insures that the incoming measurement signals are as accurate as possible and aren't susceptible to fluctuations due to noise.

The thermocouple inputs then get converted into digital signals through a set of 3 AD7794s, which are low power, 24-bit, 6-channel, differential Σ-Δ ADCs. The flow sensor input goes straight to an AD7680, which is a single-ended, 16-bit, 1-channel PulSAR ADC. The board also houses a surface-mounted 16-bit temperature sensor to be used in cold-junction-compensation calculations. Figure 6 shows the signal conditioning circuit used for the thermocouple inputs.

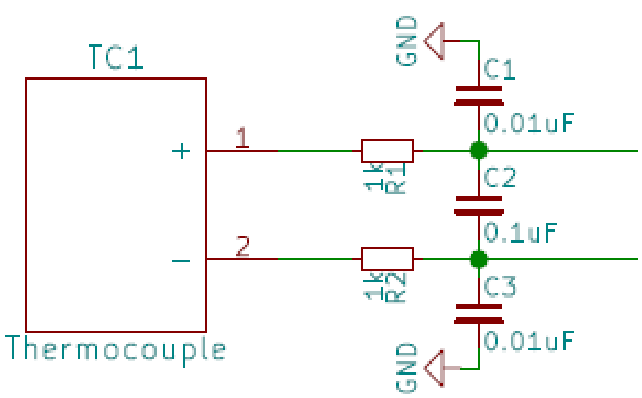

Figure 7 - Thermocouple signal conditioning

For the controller section we elected to go with an FPGA as it better fit the nature of the project since it can sample and process multiple signals from varying types of sources simultaneously. According to [2][3] FPGAs are more flexible, power-efficient, and reconfigurable than traditional data acquisition systems. The controller unit is a ZTEX FPGA board that has a Spartan 6 FPGA, Cypress EZ-USB controller, and 100 available external GPIOs. The FPGA can be programmed using any hardware description language (HDL) by generating a bit file through Xilinx ISE and implementing it using the provided FWLoader program for the board. The board is connected to the PC through USB and is capable of throughput rates up to 480 Mbits/sec. The PC runs the host software that handles the data collection, conversion into real values (including cold-junction-compensation), and storage into files. The embedded software running on the FPGA is detailed by Figure 7.

The FPGA board is powered by either an external power source or USB and is has a power supply onboard. The PCB is powered by either an external power source or the FPGA board's 3.3V output.

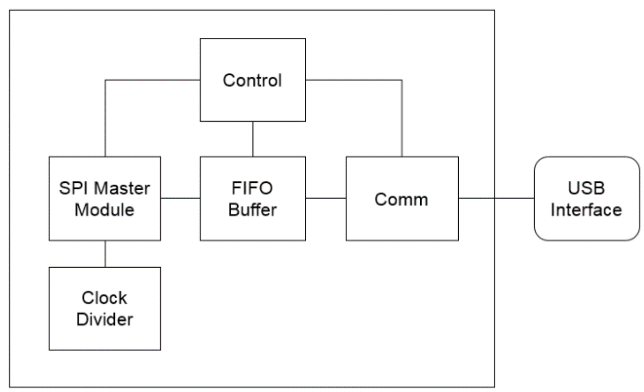

Figure 8 - Embedded software block diagram

VII. CONCLUSION

This project has been a long road of design changes. When we first started we imagined a much smaller duct with many more temperature sensors. We initially thought the heater output would be high and were planning to use a variac to control the power but then found out the power output would be relatively low and so we used a DC supply and boost converters. We changed our air measurement device multiple times from an orifice plate to a pitot tube then a rotameter and a hotwire sensor. We planned on building our own DAQ but needed data from it to build other parts of the project and so had to buy a pre-made one while we built our own. The requirements of our device constantly changed over the year as calculations we refined and simulations were adjusted moving the ranges our device must operate within. While each change delayed our progress we also performed a vital role for the project. Any future group who takes on this task will be better equipped to handle it because they will have our knowledge from what we did and so will not need to make our mistakes. And our end product while not a perfect machine does archive the goals it set out to accomplish. We are grateful to all of our counterparts on the mechanical team for all the hard work they have put into this project and for the guidance that our heat transfer specialist Yingying Wang and our customer/guide Don George.

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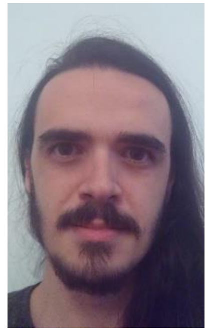
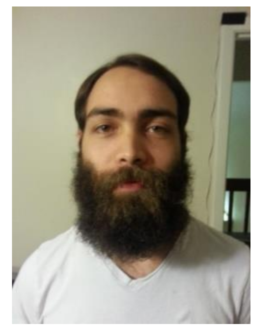
BIOGRAPHY



Patrick Armengol is receiving his B.S. in Computer Engineering from the University of Central Florida. His interests include FPGA design, system architecture, hardware security, network security, and reverse engineering. He has published research on WiFi localization and privacy with Dr. Kemal Akkaya at Florida International University and done an independent study on IoT security and firmware RE with Dr. Yier Jin at UCF. Following graduation he intends to travel and gain industry and lab experience before returning to graduate school for a doctorate degree.

Adam Blair is receiving his B.S. in Electrical Engineering from the University of Central Florida.



Eric Guest is receiving his B.S. in Computer Engineering from the University of Central Florida. He is presently working at Lockheed Martin Mission Systems and Training as a systems engineer.

Jinjin Lin is receiving his B.S. in Electrical Engineering from the University of Central Florida. His research interests include integrated circuit design, filter design, and amplifier power design in RF. He has done an independent research in filter design of the radio frequency with Dr. Gong Xun at UCF.