Protecting the future of particle physics

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I ABSTRACT

The upgrade of the ATLAS ITk strips detector for HL-LHC will use custom PCBs (powerboards) for on-module DC-DC conversion, HV switching, and monitoring. To ensure high reliability, quality control (QC) testing for the powerboards to be installed on ITk Strip barrel modules is necessary. The QC tests include thermal cycling, burn-in, and electrical tests of the low voltage (LV), high voltage (HV), and monitoring functions of the powerboard. The ATLAS group at LBNL developed a massive test crate that is able to perform electrical and thermal tests on 200 powerboards simultaneously. The test crate is crucial for the timely delivery of this component of the upgrade, and the powerboards' safety within the test crate is paramount. This protection is achieved in the form of an interlock system, which acts as the last line of protection to the powerboards and testing hardware in case of any failures in the system. When triggering, the interlock system should be able to shut down the chiller that controls the crate ambient temperature, the LV source, and the HV source. Additionally, it should prevent users from turning any of those elements back on until the interlock system is no longer triggered. In order to implement the interlock system, the sensors that it uses to monitor the crate must have their parameters fit using a data collection procedure. Following this procedure, sensor fits have been implemented for temperature, humidity, and dry air flow, and the interlock now facilitates the crate's safe operation.

II INTRODUCTION

ATLAS (**A** **T**oroidal **L**HC **A**pparatu**s**) is a general-purpose detector at the LHC (**L**arge **H**adron **C**ollider) that has been involved with fundamental discoveries in particle physics during the past few decades, including the detection of the Higgs boson in 2012. Sitting at an impressive 46 m long, 25 m in diameter, and 7000 tonnes, no particle detector has ever been larger in volume. It resides in a cavern 100 m underground near the main CERN site in Switzerland. Particle beams accelerated by the LHC collide in the center of the ATLAS detector, breaking into new particles that scatter in all directions. A series of detecting subsystem layers in the walls of ATLAS measure the momentum, energy, and path of the particles that hit it through a magnet system that bends the particle paths. Since the detector receives countless hits, it digests the particle data using a "trigger" system that identifies what events should be recorded. Data-acquisition (DAQ) and computing systems are then able analyze the recorded collisions.[1]

A major upgrade of the ATLAS detector is planned, with installation in the second half of the decade. This upgrade is a part of the High Luminosity Large Hadron Collider (HL-LHC) upgrade, which aims to accelerate physics research by increasing the particle density of the beam, which increases the amount of data. However, the additional radiation and data from this upgrade will require new systems, including an all-silicon Inner Tracking Detector (ITk) with strip and pixel systems, as silicon sensors are very radiation tolerant and have low occupancy. The strip barrel modules need powerboards for DC-DC conversion, HV switching, and monitoring. The powerboards, a component of the ITk, are printed circuit boards built from a flexible polyamide core and loaded with SMDs and bare die components and chips. LBNL is the lead institute in the design and production of these powerboards and will oversee the fabrication of a total of about 10,000 parts, and must do so with a high level of reliability. The ATLAS group at LBNL developed a massive test crate that is able to perform electrical and thermal tests on 200 powerboards simultaneously. This test crate is crucial for the timely delivery of this component of the upgrade. Additionally, each powerboard costs nearly $500 USD in components alone, not accounting for RD costs, and requires collaboration between multiple facilities (e.g. LBNL, AmTech, etc.) to create and mount, so their safety within the test crate is paramount. This protection is achieved in the form of an interlock system, which acts as the last line of protection to the powerboards and testing hardware in case of any failures in the system (power loss, overheating, etc.). When triggering, the interlock system should be able to shut down the chiller that controls the crate ambient temperature, the low voltage to the crate, and the high voltage to the crate. Additionally, it should prevent users from turning any of those elements back on until the interlock system is no longer triggered.[2]

The brain of the interlock system is a specialty PCB (**p**rinted **c**ircuit **b**oard) (Figure 1) designed by Zhicai Zhang, which can monitor resistor type (e.g. NTC) or voltage type signal, trace sources of input failures, send active low/high interlock signals to the devices, and self-run without any additional software. The crate temperature and humidity are monitored via climate sensors, and the interlock PCB reads the analog temperature/humidity sensor input signals and sends interlock output signals to the LV/HV source and chiller. Interlock is hardware-based with analog signals as input and uses comparators/logic gates to take simple OR of monitored signals as interlock signals. If all the input signals are within thresholds (low) and the tactile switch on the board is pressed, the chiller, LV, and HV will be ON. Otherwise, they will be OFF.

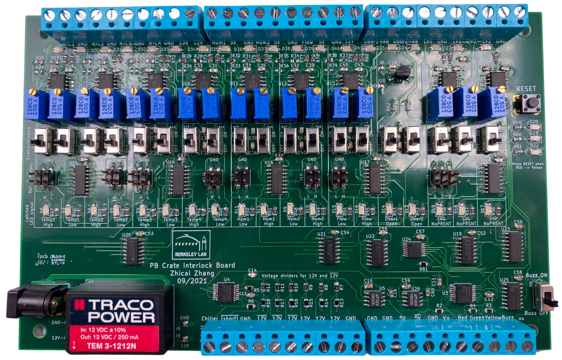

Figure 1: The interlock PCB, designed by Zhicai Zhang

The PCB must monitor the following channels: 3 NTC temperature sensors[3], 2 HUM relative humidity (RH%) sensors[4], and 1 FLOW air flow sensor[5]. Potentiometers are soldered to the board that can be tuned to restrict the range of interlock operation; if the voltage or resistance signals exceed the high threshold or fall below the low threshold, the board will shut down all outputs, which directly power the low voltage, high voltage, and chiller. A model range for the sensors can be found on the datasheets for each sensor component, and these can be converted to voltage and resistance values.

III METHODS

To fully commission the interlock system, the deviation between the model sensor and the actual analog sensors attached to the board must be determined, a fit for the actual sensors must be created, and that fit must be used to tune the thresholds for safe operation. There are three different types of sensors that need to be examined: NTC, RH%, and FLOW.

A NTC

Temperature will be lowered 5 °C starting at 40 °C until reaching -45 °C. Temperature data (in the form of voltage) will be collected every 30 seconds from the NTC port on the interlock PCB using a multimeter. Once the temperature reading has stabilised at a given value (same reading within 0.01 V for at least one minute), the chiller temperature will be lowered. At each measurement, the temperature as measured by the Grafana temperature sensors already affixed to the crate will be recorded. The temperature data from the interlock port will be fit using graphing software, and this equation will be compared to the model fit equation and any set parameters will be determined. This fit will then be used to tune the PCB's potentiometers, and the quality control (QC) procedure will be executed using the interlock.

B RH%

Dry air supply to the crate will be lowered incrementally using the physical dry air dial, and humidity will be measured using the HUM port on the interlock PCB using a multimeter. This will be done for a full humidity range of 0 to 35%, with the dry air supply tuned to achieve each data point (in the form of voltage). At each measurement, the humidity as measured by the Grafana humidity sensors already affixed to the crate will be recorded. The humidity data from the interlock port will be fit using graphing software, and this equation will be compared to the model fit equation and any set parameters will be determined. This fit will then be used to tune the PCB's potentiometers, and the quality control (QC) procedure will be executed using the interlock.

C FLOW

Dry air supply to the crate will be increased in increments of 0.1 CFM from 0.1 CFM to 2.1 CFM using the physical dry air dial. Air flow data (in the form of voltage) will be collected every 30 seconds from the FLOW port on the interlock PCB using a multimeter. Once the air flow reading has stabilised at a given value (same reading within 0.01 V for at least one minute), the dry air supply will be increased. The air flow data from the interlock port will be fit using graphing software, and this equation will be compared to the model fit equation and any set parameters will be determined. This fit will then be used to tune the PCB's potentiometers, and the quality control (QC) procedure will be executed using the interlock.

IV RESULTS

A NTC

While the interlock board reads a voltage-type value for temperature, the NTC actually provides a resistor-type value, in contrast two the humidity and air flow sensors that provide voltage-type values in alignment with the interlock board readings. For most NTC thermistors, the Steinhart-Hart equation[6],

$$\frac{1}{T} = a + b \ln R + c(\ln R)^3, \tag{1}$$

can be manipulated when $a = \frac{1}{T_0} - \frac{1}{B}\ln R_0$, $b = \frac{1}{B}$, and $c = 0$ to yield

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B}\ln\frac{R}{R_0}, \tag{2}$$

where B is measured in Kelvins, T_0 is the temperature at 25 °C in Kelvin, and R_0 is the resistance at T_0 in Ω. Solving this equation for R yields

$$R = R_0 e^{B(\frac{1}{T} - \frac{1}{T_0})}. \tag{3}$$

The NTC sensor datasheet[4] lists values for B and R_0 at $T_0 = 25$ °C $= 298.15$ K: $B = 3984$ K and $R_0 = 10000$ Ω. R can be converted to a voltage reading V_{NTC} by noting that there exists a voltage divider

$$V_{out} = \frac{V_{in}R_2}{R_1 + R_2} \tag{4}$$

with $V_{in} = 12$ V, $R_1 = 50000\ \Omega$, and $R_2 = R$, per the schematic of the interlock board[7]. It follows that

$$V_{NTC} = \frac{12R}{50000 + R} \tag{5}$$

These equations establish a model for the NTC behavior that should be seen during data collection. Graphing the NTC data yields the following graph (Figure 2):

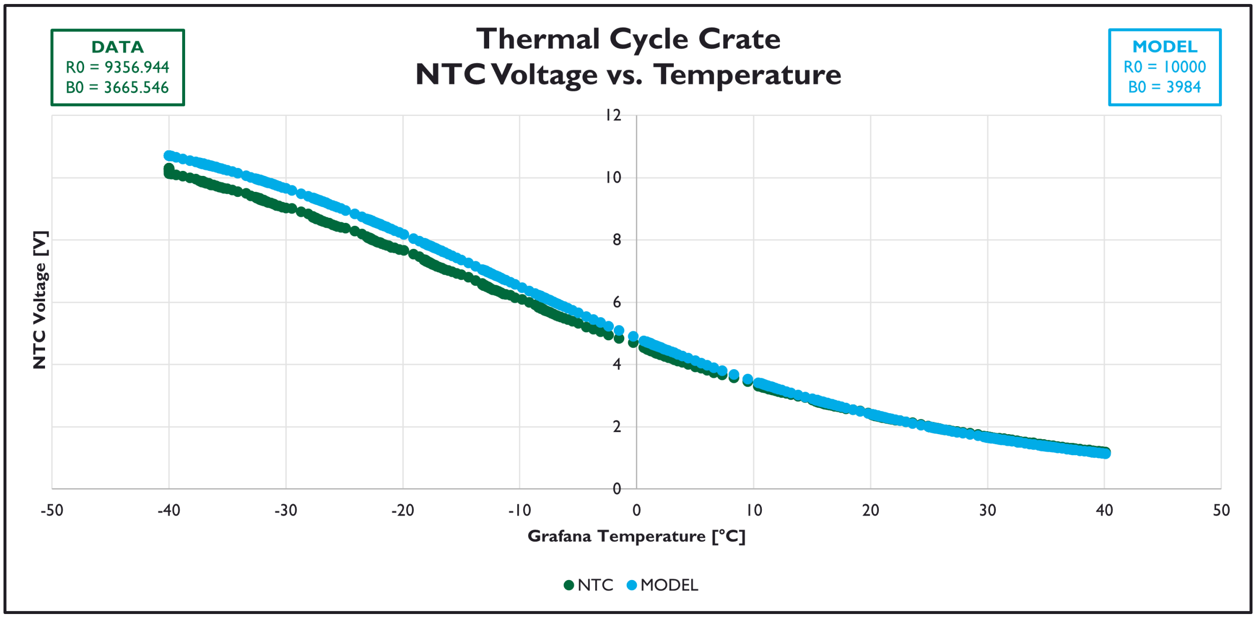

Figure 2: NTC Voltage vs. Temperature data

Fitting values for B and R_0 to the collected data yields $B = 3665.546$, a 6.43% error, and $R_0 = 9356.944$, a 7.99% error.

B RH%

The RH% sensor datasheet[3] lists an equation for the output voltage,

$$V_{out} = V_{in}(0.0062RH + 0.16), \tag{6}$$

with $V_{in} = 5$ V, where RH is measured in %. This equation establishes a model for the RH% behavior that should be seen during data collection. Graphing the RH% data yields the following graph (Figure 3):

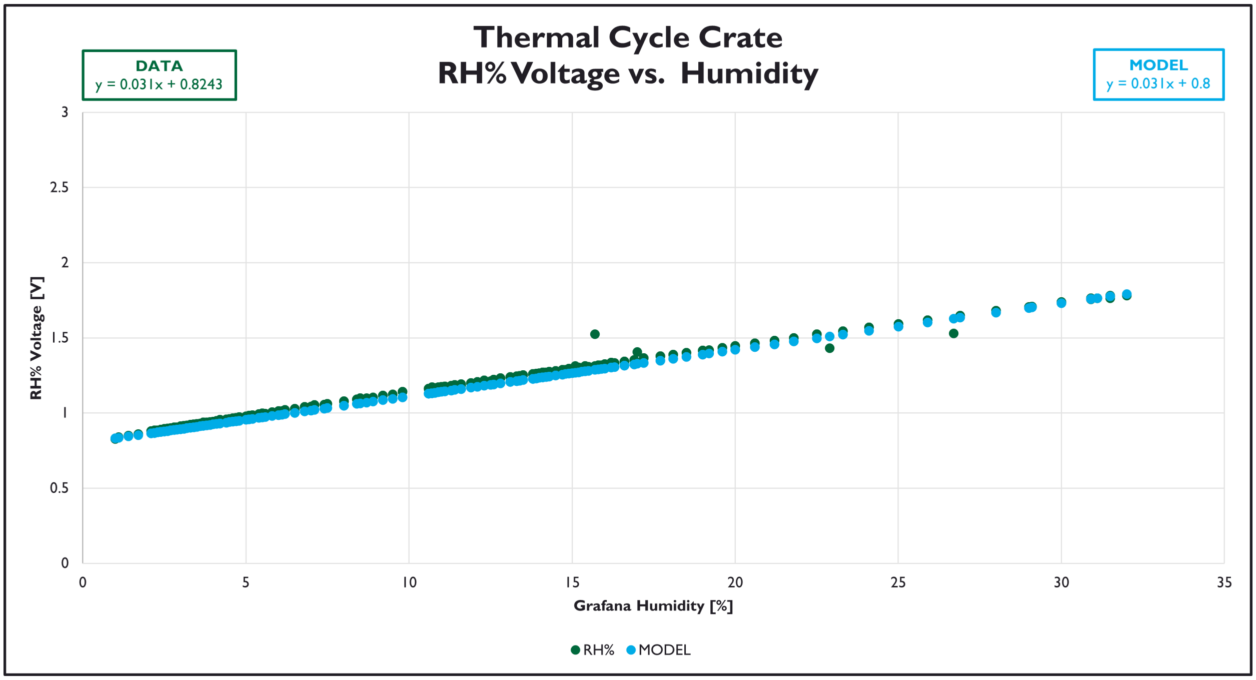

Figure 3: RH% Voltage vs. Humidity data

The datasheet model is a linear fit with a slope of 0.031 and an intercept of 0.8, and the fitted values for the collected data yields a slope of 0.031, a 0% error, and an intercept of 0.8243, a 3.04% error.

C FLOW

The FLOW sensor datasheet[5] lists an equation for the output voltage,

$$V_{out} = V_{supply}(\frac{FLOW + 10}{212.5} + 0.1), \tag{7}$$

with $V_{in} = 5$ V, where $FLOW$ is measured in CFM. This equation establishes a model for the FLOW behavior that should be seen during data collection. Graphing the FLOW data yields the following graph (Figure 4):

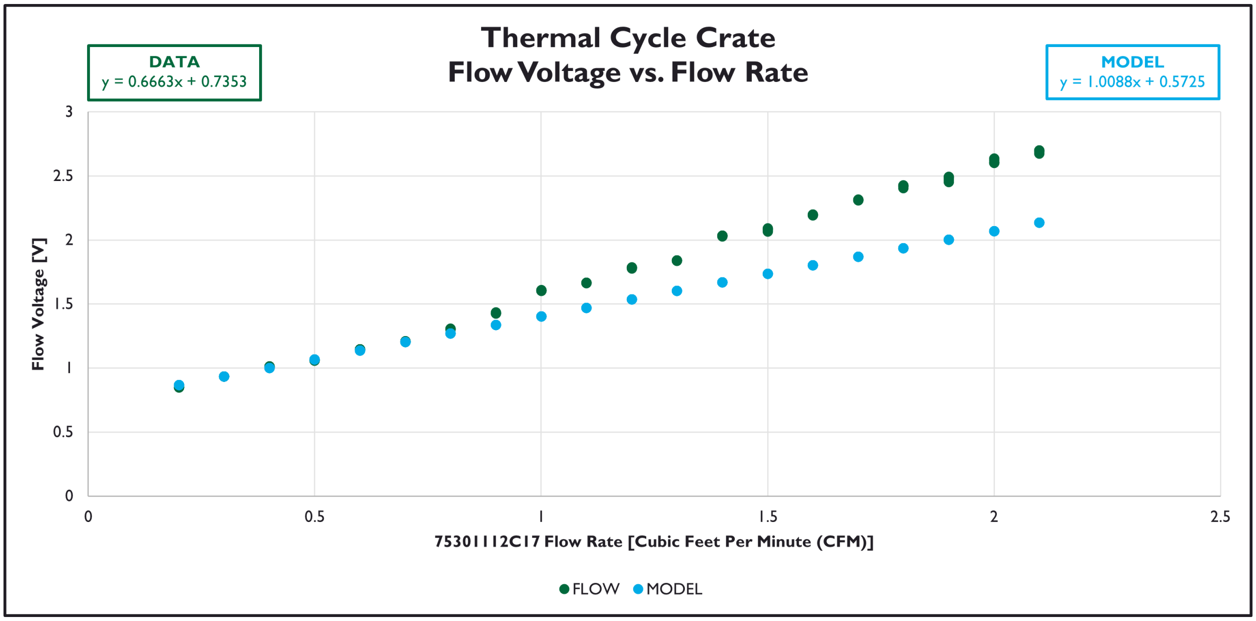

Figure 4: FLOW Voltage vs. Flow Rate data

The datasheet model is a linear fit with a slope of 1.0088 and an intercept of 0.5725, and the fitted values for the collected data yields a slope of 0.6663, a 34.0% error, and an intercept of 0.7353, a 28.4% error.

V DISCUSSION

A NTC

The NTC fit is extremely close to the model, which means we could use the datasheet values for B and R_0. When tuning the NTCs on the interlock board, the two different sides of the crate must be taken into account: the passive side and the active side. The passive side is where the carrier cards (which carry groups of ten powerboards) reside, and will experience the full range of temperature operation (-40 °C to 40 °C). The active side is where the active boards, reusable PCBs where all the testing circuits are hosted and the output signals from the powerboards are sent and reside, and will not go below freezing, experiencing a temperature range of 0 °C to 40 °C.

In the current crate configuration, NTC1 and NTC2 are on the passive side, and NTC3 is on the active side. Since the NTC range is -40 °C to 150°C[4], NTC1 and NTC2 will be unable to read the lower limit of the range of temperature operation, so it is unnecessary to set a lower threshold. The upper threshold for these NTCs is roughly 0.885V, or 47.25 °C in the NTC fit. Since 0 °C is within the NTC range, NTC3 needs a lower and upper threshold. The lower threshold for NTC3 is roughly 4.8V, or -3 °C in the NTC fit, and the upper threshold is roughly 0.885V, or 47.25 °C in the NTC fit.

B RH%

The RH% fit is also extremely close to the model, which means we could use the datasheet values for the slope and intercept. In order to protect the circuitry on both sides, RH% should not exceed 30%. In the current crate configuration, HUM1 and HUM3 are on the passive side, and HUM2 is on the active side; NTC4 was repurposed as HUM3. A lower threshold is not needed for RH% monitoring, since the lowest humidity feasible is ideal. The upper threshold for HUM1 and HUM3 is roughly 1.5 V, or 21.75% in the RH% fit. The upper threshold for HUM2 is roughly 1.7 V, or 28.25% in the RH% fit. The difference between these two thresholds is determined by the current crate configuration, since the RH% measurement tend to be higher on the active side due to insulation and materials.

C FLOW

Before roughly 1 CFM, the FLOW fit is extremely close to the model; however, after 1 CFM, there is a sizeable deviation between the data and model. This is likely due to the construction of the dry air flow sensor itself, and the way it is currently connected to the dry air supply. Thus, the FLOW fit should be used. An upper threshold is not needed for FLOW monitoring, since higher dry air flow decreases humidity and promotes the safety of the crate's electronics. The upper threshold for FLOW is roughly 1.5V, or 1.15 CFM.

VI CONCLUSIONS

While the sensors have been adequately tuned and the interlock is now ready for operation, there are a couple concerns for the fits developed.

For the NTC and RH$ sensors, the location in the crate they are affixed to matters. Since the passive side is much larger than the active side, and houses significantly more electronics, two sensors of each type are affixed on opposite corners of the passive side. This leaves only one sensor of each type affixed in the active side, which leaves it susceptible to a failure in the sensor with no backup to continue interlocking. In an ideal world, there would be enough sensors of each type to fully cover each side of the crate, but that is not feasible for analog sensors, and the current method is exhaustive enough that the electronics are reasonably safe. Additionally, there are digital sensors within the crate that notify users when conditions become unsafe, that allows for the user to add an extra layer of protection to operation.

For the FLOW sensor, the construction of the sensor is not perfectly airtight, and the adequacy of the tape used to make the sensor more airtight varies. This means that the voltage may be higher at lower flow rates than the FLOW fit implies, and the crate may not be receiving enough dry air to keep the humidity in check. However, the FLOW sensor works in tandem with the RH% sensors in monitoring and interlocking the humidity of the crate, so variability in the air flow rate threshold holds less impact than variability in the temperature threshold would.

With the confidence that the electronics of the powerboards are safe, the production of the replacement of the ATLAS Inner Tracker detector (ITk) can continue as planned. With pre-production concluding and production looming on the horizon, it is a great comfort to know that the hard work of countless career scientists will not be squandered due to temperature or humidity fluctuation. Looking forward to the latter half of this decade, the HL-LHC upgrade will mark a new horizon for particle physics experimentation, and take the work of scientists across the globe beyond the Standard Model.

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