Princeton University

Senior Thesis

Mid-Year Interim Report

A Wired Sensing Suite for Data Center Climate Monitoring

Author:

Ryan O'Shea

Supervisor:

Prof. David Wentzlaff

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Engineering in the

Department of Electrical Engineering

January 12, 2016

This paper represents my own work in accordance with University regulations.

Ryan C O'Shea

Ryan C. O'Shea

Contents

Chapter 1

Introduction

1.1 Motivation

In the past decade, the paradigm of personal computing has undergone a major shift. Mobile devices wielding the same computational power of desktop PCs have become increasingly prevalent in developed parts of the world. As the capabilities of both mobile and other personal devices have grown, more complex and compute-intensive applications have been developed to serve customers using faster devices. These two areas of growth have not progressed at the same speed, however, and as such, applications powered by the Internet have moved their compute workloads from consumer devices to "The Cloud" — to servers and computer clusters hosted in large data centers. In order to provide useful experiences to customers, applications need to leverage computational power beyond the limited capabilities of a low-power mobile device or even a laptop PC. So, no longer limited by the speed of personal devices, application developers can continue to provide increasingly complex services by deploying their computational backends on servers in a data center.

An entire business sector has emerged from this change. Internet companies frequently pay for computational power and storage space with which to power their applications, either obtaining these from a third party data center provider like Amazon or via the establishment of their own data centers, an option typically reserved for the largest technology companies due to the prohibitive cost of building and maintaining a data center.

Meanwhile, the speed of CPUs has grown — and transistor size has shrunk — generally in accordance with Moore's Law, but power consumption has not followed the same downward trend expected by the law. Instead, supply voltage has remained nearly constant and as such, building faster processors in recent years has necessitated increases in energy consumption and heat output per chip [1]. Following this, the most substantial limiting factor in the growth of data centers is power consumption — both directly powering computational equipment and powering the massive systems required to keep them cool. Data center power consumption doubled worldwide from 2000 to 2005 [2] and quadrupled in the decade prior to 2012 [3]. Even though this growth did not live up to decade-old predictions [4], data centers still consumed $4.5B in electricity each year in the US by 2006 [5] and have only expanded their footprint since.

More important even than the overall rate of growth of data center energy usage is the proportion of the energy used that goes towards cooling rather than directly to work. By some estimates, cooling can consume 40-45% of a data center's total electricity usage [6], which has turned cooling efforts and systems from necessary, though secondary, features of these data centers to an aspect of their design as important as the servers and network themselves. Any system as large, complex, and expensive as a data center cooling system is critically concerned with its efficacy. If any areas of the data center's "data hall" (the room which actually houses the servers and is the target of nearly all cooling efforts) receive uneven treatment from the cooling apparati, prolonged operation could result in permanent, costly damage to computing hardware or the facility itself. This could come in the form of "hot spots," in which hardware in a small part of the facility is allowed to heat past the low temperatures required for continuous operation under load. It could also take the form of moisture collecting via condensation in more complicated cooling schemes, the result of which could be electrical damage to hardware or even a fire hazard. On a relatively unrelated note, server racks with moving components — like spinning hard disk drives — might suffer from unwanted vibration that could damage components in similar ways.

In response to these concerns, and with demonstrated interest from the Princeton University High Performance Computing Research Center (HPCRC),[1] this project aims to create an inexpensive means of monitoring the climate in a data center to allow site operators to identify possible problems as they arise and to ensure that their computing resources can operate safely at full capacity.

1.2 Background

This project began in 2014 as a student independent work project to design a sensor board (both circuit and PCB layout) to allow some sort of controller device to communicate with small, inexpensive temperature sensors over the I^2C bus protocol. The circuit also incorporated a series of switches to allow for easy configuration of the sensor device's address on the I^2C bus, which is required to be unique for each device on the bus.

[1] A nearby data center serving Princeton University faculty and students

The initial work was performed by Rahul Subramanian '14 [7] under the guidance of Prof. David Wentzlaff, under whose control it remains. It was continued by Peter de Groot '15 as another independent work project, where the designs were miniaturized and manufactured as boards and a working subsystem of sensors connected to a controller was deployed and successfully displayed its gathered data via a simple web application running on the bus master device. Further efforts were contributed by Felix Madutsa '19 to digitally reconstruct some of de Groot's work and expand on the web application used to display sensor data.

Further details on the system design and the contributions of the author's predecessors are provided in Chapter 2.

1.2.1 Goals for Current Project Iteration

This iteration of the project aims to move the components of the system to a state that can be more easily and cheaply mass-produced than previous versions. It will fully develop as-yet-nonexistent capability to operate beyond a small-scale system involving a single controller device attached to an array of sensor boards, instead orchestrating the operation of many instances of these controller-sensor subsystems as one functional system. It also aims to deploy the final design in a live data center environment, likely the Princeton HPCRC. If possible, the design should begin to incorporate capabilities for monitoring additional metrics like humidity and vibration. Lastly, it aims to build a web application for managing a deployed instance of the climate monitoring system so that site operators can both utilize the system for climate monitoring and add and modify their instance of it.

1.3 Related Work & Project Position in its Category

Climate monitoring of data centers is an active field of research and development, so this section aims to recognize related efforts in the field and explain some of the design choices made in this attempt at a solution. The latter half of this section makes limited use of prior research already done in de Groot's iteration of this project, found in [8].

Most importantly, the use of a wired network to link the sensors together was a key design choice. The primary factor in this decision was cost. Keeping the cost of the sensor suite as low as possible is a major concern for this project, as each deployed instance of the system could consist of dozens or hundreds of sensor boards collecting data at various locations across a data center's data hall. Each increase in the price of an individual sensor board is amplified across all boards, and wireless communication equipment would at the least on the order of double the cost of each sensor board. Wired communications, however, allow us to make use of much cheaper cables to carry data between each sensor and the controller. The signal integrity across a wired connection is also likely higher, especially on a relatively low-frequency bus protocol like I^2C. Adding wireless communications to the board would also necessarily increase the size of the board, especially since it would then need to find room for the wireless transmitter itself and some sort of microcontroller as well, which would be required to interface between the sensor's I^2C protocol and the controls of the wireless transmitter. This increase in size and price (especially since microcontrollers are much more expensive than even the most expensive components on the current version of the board) would make the sensor board increasing impractical as a small, inexpensive, unobtrusive addition to a server rack, which this system aims to be.

Regarding other methods of data center climate monitoring, IBM proposed a much different solution involving a roving platform capable of collecting data as it wandered around a facility [9]. Rather than a low-cost network of devices scattered across a room, this solution relied on very low quantities of relatively expensive equipment. This system has the advantage of allowing data center operators to diagnose a problem area hyperspecifically by moving the sensing equipment directly to that area, though as noted in [8], it also has the significant disadvantages of having very low time resolution due to the physical movement needed to record data in different locations as well as operational interference caused by automated vehicles traveling in the same space as humans.

Another, more similar example to the system laid out in this paper is Raritan's data center climate monitoring solution [10]. Raritan sells a series of sensors and controllers that can mount on to a server rack. In their system, each temperature sensor hangs from one wire, rather than having multiple sensors placed along a single wire, as they are in our system. While this allows for greater plug-and-play capabilities, cable clutter would quickly become an issue if a data center would like to position many of these sensors, say, along a vertical line down the side of a server rack. Also, it seems that Raritan's sensors need to be connected to a rack outfitted with their "intelligent rack" technology, which obviously necessitates a more sizeable investment on the part of the data center operator.

Geist offers a number of rack-based climate monitors — that is, systems that slide into a slot in a server cabinet like server would — which have onboard temperature sensors and the capacity to attach up to four external sensors for expanded sensing capability [11]. These systems are larger and significantly more expensive, due to their more substantial footprint. They also require data center operators to possibly sacrifice space in their server cabinets to fit the monitor, as opposed to our side- and top-mounted solution, which simply attaches to the exterior of a cabinet. The units also host a web application locally and provide access over an ethernet connection to the outside Internet, which is a feature of the de Groot implementation of this project, but which we are replacing in this iteration with a global web application handling multiple sets of sensors.

The takeaway from this brief survey of the current market landscape is that climate monitoring for data centers is an active area of research and that even professionally designed systems come with drawbacks, expenses, and tradeoffs. Though the industry is relatively standardized, each data center is different, and each operator may have differing thoughts on what role monitors should play in the space they control. As such, there is great room for a variety of approaches, so our minimalist design might serve the market well.

Chapter 2

Fall Term Progress

2.1 Assessment of Existing System

This section describes in detail the state of the climate monitoring system before this term's work was conducted, as many of the design details remain relevant or perhaps unchanged.[1]

2.1.1 Sensor Board Instrumentation Circuit

TMP175 Sensor

The most fundamental component of our system — and the one towards which the majority of this term's efforts were directed — is the circuit and board design for the actual sensor(s). The main component is a simple, inexpensive digital temperature sensor. The one chosen for this project is

[1] This entire section is based on the work in [7] and [8]. Some additional work was provided by Felix Madutsa, though no written source exists to document that work. For brevity, further citations to this material may be omitted, and the description provided references the state of the system as it was when this iteration of the project began in September 2015, so differentiation may not be made between the contributions of each author to the project, and descriptions will focus on the combined design of the final de Groot/Madutsa version.

a Texas Instruments TMP175 chip in a surface mount LM75 package [12]. The sensor provides its readings via the two-pin I^2C bus, which of course implies that a secondary, master device be present in the system to read values from the sensor.

Addressing

Multiple TMP175 sensors can be attached to the same I^2C bus by varying the address of each sensor on a given bus to avoid collisions. The sensor has three addressing pins, each of which use trinary logic (ground, reference voltage, or floating voltage), providing a total of 3^3 or 27 possible addresses. Therefore, we can place up to 27 TMP175 sensors on a single bus.

To accomplish this, the circuit incorporates six DIP switches. Each address pin of the sensor is controlled by two switches. One, when switched on, pulls the pin high via a pull-up resistor. The other, likewise, pulls the pin low via a pull-down resistor. Leaving both switches off results in a floating/random voltage, and the third logical option for the pin. The presence of the pull resistors have the added benefit of preventing a short circuit if both switches are turned on.

Connectors

The circuit uses a 10-pin connector, which in turn connects to a 10-wire ribbon cable, to provide power and I^2C data from the controller. The 10-pin design is used for two reasons. First, the type of cable used is inexpensive. Second, the arrangement of pins assures that if a the ribbon cable connecter were to be attached to a board in the wrong orientation, no permanent damage would be done to the board.

Other components

The circuit has an LED which illuminates to confirm that the device is receiving power. It also has two decoupling capacitors between power and ground, one to prevent against short-term power fluctuations and another with greater capacitance to prevent against longer-term fluctuations.

Circuit Diagram

The diagram for the circuit as it stands currently is shown in Figure 2.1. This circuit only has a few very minor differences from the version in the de Groot iteration of the project.

2.1.2 PCB Design

The circuit described is produced on a small 2-layer printed circuit board. The board only has components on one side for reduced costs. It has primarily surface-mount components for easy assembly, but the header for the ribbon cable is a thru-hole component. The design is shown in Figure 2.2.

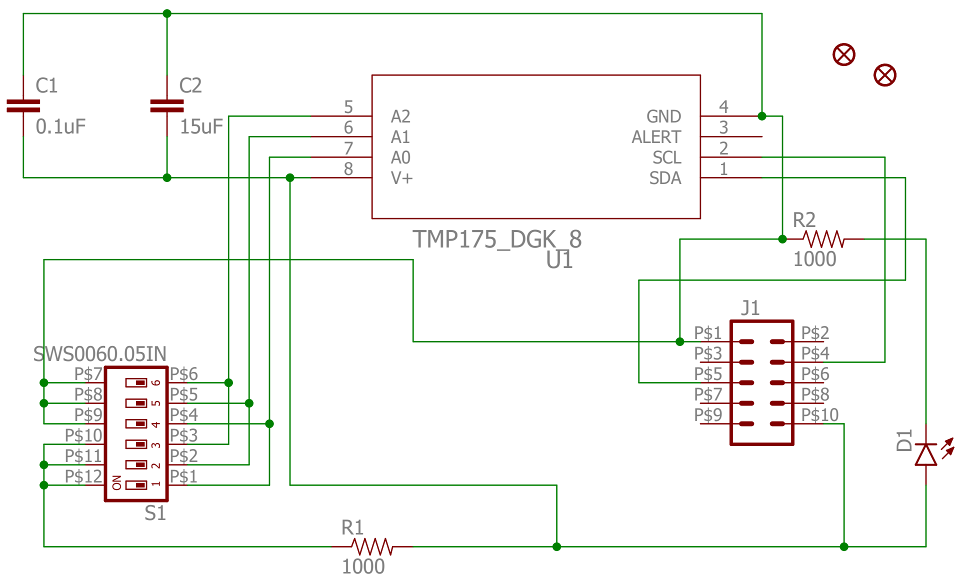

Figure 2.1: Current instrumentation circuit diagram for sensor board. To clarify, `J1` is the cable header.

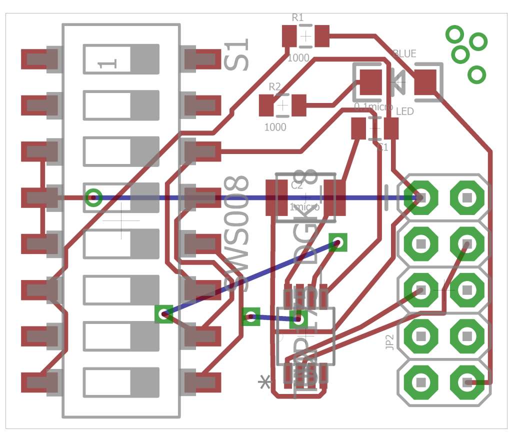

Figure 2.2: Original design for sensor board PCB. Dimensions: 1.1" × 0.9"

We identify some issues in this design:

- Non-45° traces are used
- DIP switch component is too large
- Non-uniform vias
- Two layers used for routing, but large wasted areas present
- Thru-hole component is an obstacle for cheap automated assembly

These concerns are addressed by the new design, which can be found in §2.2.

2.1.3 BeagleBone Black Controller

To manage the gathering of data from the sensors, a BeagleBone Black running custom software is utilized. The BeagleBone is connected to a cape to aid in providing the proper connections.[2] The software periodically queries the full address space of the TMP175 sensors and detects the addresses of each sensor connected to the bus. It then periodically gathers temperature readings from those sensors, keeping track of which sensor provided each reading. The BeagleBone supports two I^2C buses, so in theory each BeagleBone can manage up to 2×27 or 54 sensors.

In the current implementation, this data is saved in an SQL database and presented to users via a web application that is hosted via an instance of the Apache webserver running on the BeagleBone. The BeagleBone need only be connected to the internet via its Ethernet port, and the application can be accessed by visiting the BeagleBone's IP address from any web browser.

[2] The details of this setup, which have been omitted for brevity, can be found in [8].

Obviously, this method of displaying climate data is limited to one sensor-controller subsystem, as the web application can only display the data provided by the sensors the BeagleBone is physically connected to. A solution for expanding past this limitation is outlined in §2.3.

2.1.4 Full Sensor-Controller Subsystem

The full system — consisting of one BeagleBone, up to 54 sensor boards, the cabling running among them, and an Ethernet connection to the Internet, would be arranged on a server cabinet in a data center as is shown in Figure 2.3.

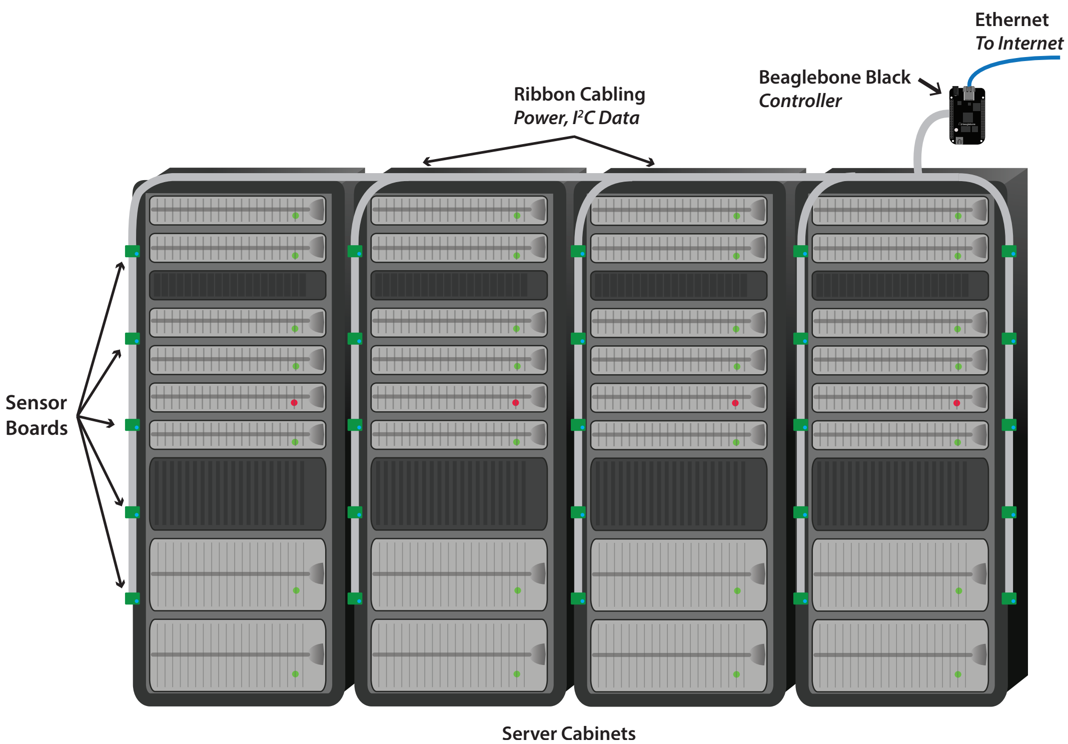

Figure 2.3: Potential layout of a sensor-controller subsystem on a group of server cabinets

The cables and sensor boards can be mounted to the exterior of the data center using any means

(Velcro® adhesive pads would work well, since the boards themselves only have components on one side).

The design of the subsystem remains effectively unchanged in the current iteration of the project. Only the sensor board form factor changes relative to the above version.

2.2 Sensor Board Miniaturization

The majority of the work carried out this term focused on preparing the sensor board for inexpensive mass production. A few priorities were designated for the redesign beforehand, including:

1. Use only surface-mount parts
2. Miniaturize the design as much as possible
3. Prioritize price over size when given the option

These priorities informed the decisions described below.

First, it was recognized that the cable header, rather than the DIP switches, should constrain the size of the board. So, the first change was a switch to much smaller DIP switches (from 0.1" pitch to 0.05"). We also switched from an 8 DIP switch component to one offering only the 6 needed for addressing. Next, the sole thru-hole component (the cable header) was removed in favor of a surface-mount replacement. For a brief period, we considered reducing the pitch of the cable header from 0.1" to 2mm, but that idea was abandoned upon the realization that the cable assemblies needed in that case were substantially more expensive than the 0.1" versions.[3] One other small change was made to the circuit, namely that we replaced the larger electrylytic decoupling capacitor

[3] Note that because we use a 2×5 header at a pitch of 0.1", the pitch of the cable itself needs to be half that, or 0.05".

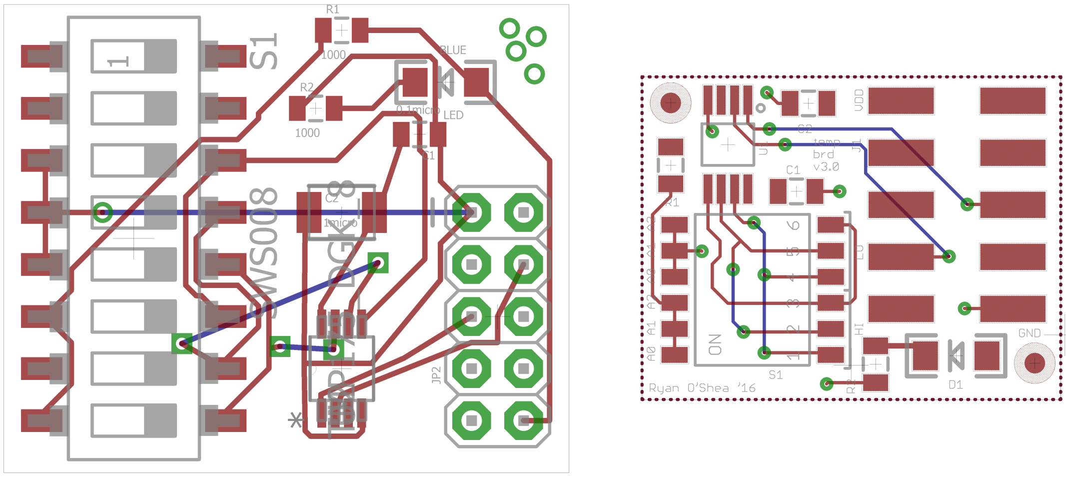

Figure 2.4: De Groot PCB (left) vs. miniaturized PCB (right)
To relative scale: 1.1"×0.9" vs. 0.8"×0.65"
Copper pours not shown for component visibility

with a ceramic one with much higher capacitance for greater protection. The final circuit diagram is shown in Figure 2.1 and a specific list of all parts can be found in Appendix A. Lastly, and just for best practices, we included copper fill pours for the ground and power signals, and ensured that all traces were aligned to a standard grid and oriented at 45° angle increments.

The new design is **47% smaller** in terms of area than the original design. It uses only surface-mount components so that the board can be easily assembled by an automatic pick and place machine. Ignoring the fixed cost of non-design-related portions of PCB fabrication and assembly, the new design **costs 20% less to fabricate** due to its smaller footprint and **34% less to assemble** due to the removal of thru-hole components.[4]. Tabulating the prices for each component,[5] the previous design comes in at \$3.57 per board, while the miniaturized version goes up a bit in price to \$4.20. Sadly, the smaller DIP switches — though they make the smaller form factor possible — are the

[4]Based on quotes for PCB fab and assembly from Advanced Circuits, given a quantity of 500 and lead time of 2 weeks

[5]Assuming a quantity of 50

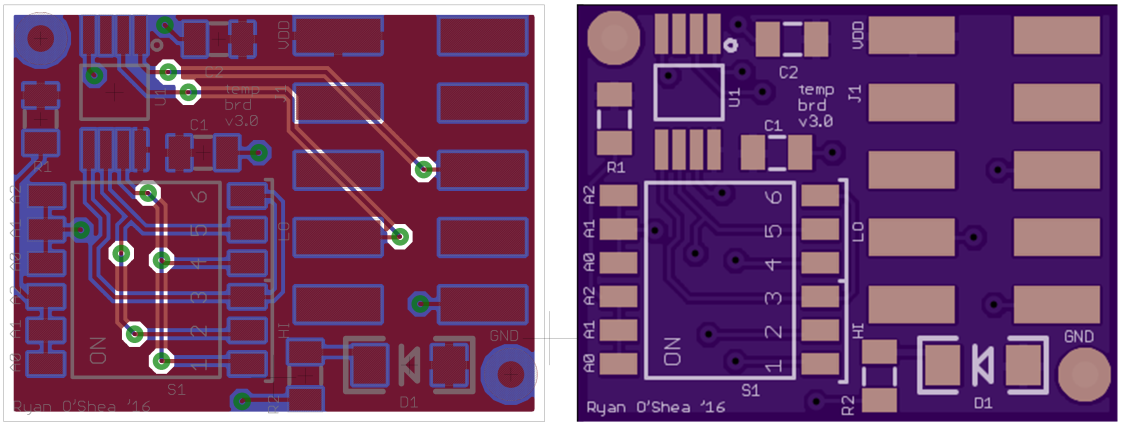

Figure 2.5: New PCB design with visible copper fill pours for power and ground (left)
Preview of fabricated board without components (right)

main driver of the price increase. Adding it all up, the new board still comes in at about 10% cheaper than the original board at a much smaller and much less obtrusive form factor. The final version of the board, with copper fills visible, can be found in Figure 2.5.

Significant time was spent in this first term gathering and comparing quotes for fabrication and assembly of the new board design. Given the large initial cost of assembling any board, no matter how small and inexpensive, the initial spin will likely utilize an inexpensive fab house and manual assembly. Full quotes for fabrication and assembly for later spins are provided for reference in Appendix B.

2.3 Top-level System Design

Moving the system to a state that is able to handle sensing for an entire data center requires the development of an architecture that can handle multiple sensor-controller subsystems operating

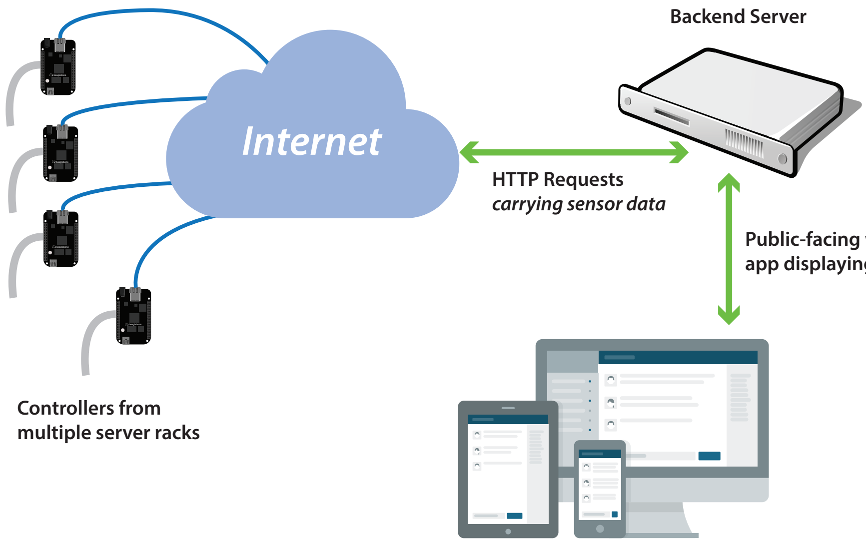

Figure 2.6: Overview of top level system: multiple subsystems managed by a server which hosts a web app

simultaneously and separately. To accomplish this goal, we have designed a top-level system that uses no additional infrastructure in the data center facility and allows for near-instant access to sensor data and powerful and flexible system management.

The system as designed is not yet implemented, but as described in §3.3, building it is one of the primary goals of the Spring term of this thesis. The top-level system is diagrammed in Figure 2.6.

Each BeagleBone will, as before, connect to the Internet via an Ethernet cable, which should be readily available in a datacenter, as network cables run above and to every server cabinet to provide their servers Internet access. However, instead of hosting a web application to display sensor data via Apache running on the BeagleBone, the device will act as a REST endpoint, serving up sensor data as JSON with the likely possibility of some form of authentication. That data will be queried periodically by a server, which, using its own representation of the various subsystems it communicates with and their sensor positions, will make sense of the incoming data and store it in a database. That server will also serve a new web application to users, which can give them the climate data collected by the sensors. That same application will allow users to manage their sensor system installations: specifying where sensors are positioned on a server cabinet, adding/removing/editing cabinets (subsystems), and any other management features that might be useful. Ideally, the climate data displayed would also be accompanied by meaningful statistics and insights about the state of the data center, though the strategy for interpreting the data has yet to be decided. Each data center could host its own web app on a dedicated management server, or the web application could be centrally hosted by a third party and provide account-based access to every data center's dashboard. Since all data transmission takes place over the public Internet, only the database storage scheme would need to change to handle both the distributed and centralized model of the top-level system.

Chapter 3

Spring Term

3.1 Expansion of Climate Sensing Capabilities

The current system only gathers data on temperature. However, data center operators may be interested in other metrics to maintain the health of their servers. Particularly, we are interested in humidity and vibration. Combined humidity and temperature sensors are quite common, but even the cheapest ones cost more than twice what the lone TMP175 temperature sensor costs, and since that cost increase is non-negligible and multiplied by each board, of which there may be hundreds in a given deployment of the system, the decision was made to postpone the addition of more metrics until a first spin of the new temperature-only board is completed.

Introducing new sensors presents additional design challenges. In order to reduce cost, the board needs to incorporate the sensors without the need for a microcontroller to handle communication or data readout from the various sensors. As such, the additional sensors would need to operate over the same I^2C bus as the temperature sensors. The address space of the two sensors could, depending on the sensor selection, collide, meaning that potentially fewer boards overall could be attached to one BeagleBone at a time. We could resolve this issue by using an I^2C switch, which would allow the BeagleBone to communicate to devices on up to 8 different I^2C buses using only one bus from the BeagleBone's perspective. That said, there may still be limits to the amount of power the BeagleBone could provide, so hardware might be needed to provide a more robust voltage source. Again, the problem is solvable, but will require additional design consideration. However, the metrics provided might provide valuable insights to the potential customer base, so they may be worth including.

3.2 Controller Codebase Redesign

The current codebase managing the BeagleBone's communication with the sensors is not very robust. Work will be conducted in the Spring term to ensure that the system is substantially more failure-resistant and supports any new features (like new sensors) that may be implemented.

3.3 Top-level System Implementation

The top-level system described in §2.3 will need to be fully implemented if the system is to be used in a production environment. To ensure a high level of quality and deliver a professional quality application, substantial development efforts will be directed towards this architecture in the Spring term.

3.4 System Production and Deployment

This project received funding from the Department of Electrical Engineering and from the School of Engineering and Applied Science via the MacCracken Independent Work/Senior Thesis fund. Much of that funding will be directed to having a full system's worth of sensor boards professional fabricated and assembled, such that they are ready to be deployed in a data center. Work will be conducted to assemble several working subsystems, and — upon the completion of the top-level system — the last design objective will be a proof of concept implementation of them working together with the user portal/server. After this, the goal is to deploy some version of the system in the Princeton HPCRC to bring the project, after many attempts, to its logical fruition. We will hopefully have a working, deployed system by May 2016. We will also work to ensure that the system be ready for immediate continuation by others once this senior thesis is concluded, so great care will be taken to ensure that all files are adequately documented and archived.

Appendix A

Sensor Board Bill of Materials

Description	QTY	Ref Des	Mfg	Mfg P/N #	Distributor	Distributor P/N #
FCI CONN HDR DUAL 0.100" SMT	1	JP1	FCI	54202-G0805LF	Digi-Key	609-4723-ND
CTS SWITCH DIP HALF PITCH 6POS 50V (0.05")	1	S1	CTS Electrocomponents	218-6LPST	Digi-Key	CT2186LPST-ND
TDK CAP CER 15UF 10V JB 0805	1	C2	TDK Corporation	C2012JB1A156M085AC	Digi-Key	445-11407-2-ND
DIALIGHT LED BLUE CLEAR 1208 R/A SMD	1	D1	Dialight	5988391117F	Digi-Key	350-3028-1-ND
VISHAY DALE RES SMD 1K OHM 1% 1/8W 0805	2	R1/R2	Vishay Dale	CRCW08051K00FKEA	Digi-Key	541-1.00KCTR-ND
SAMSUNG CAP CER 0.1UF 50V Y5V 0805	1	C1	Samsung	CL21F104ZBCNNNC	Digi-Key	1276-1007-2-ND
TI SENSOR TEMPERATURE SMBUS 8MSOP TMP175	1	U1	TI	TMP175AIDGKT	Digi-Key	296-19882-6-ND

	URL
FCI CONN HDR DUAL 0.100" SMT	https://www.digikey.com/product-detail/en/54202-G0805LF/609-4723-ND/4240461
CTS SWITCH DIP HALF PITCH 6POS 50V (0.05")	https://www.digikey.com/product-detail/en/218-6LPST/CT2186LPST-ND/267321
TDK CAP CER 15UF 10V JB 0805	https://www.digikey.com/product-detail/en/C2012JB1A156M085AC/445-11407-2-ND/3948643
DIALIGHT LED BLUE CLEAR 1208 R/A SMD	http://www.digikey.com/product-detail/en/5988391117F/350-3028-1-ND/3906503
VISHAY DALE RES SMD 1K OHM 1% 1/8W 0805	http://www.digikey.com/product-detail/en/CRCW08051K00FKEA/541-1.00KCTR-ND/1175637
SAMSUNG CAP CER 0.1UF 50V Y5V 0805	http://www.digikey.com/product-detail/en/CL21F104ZBCNNNC/1276-1007-2-ND/3886665
TI SENSOR TEMPERATURE SMBUS 8MSOP TMP175	http://www.digikey.com/product-detail/en/TMP175AIDGKT/296-19882-6-ND/1120838

Appendix B

Sample Quotes for Full Sensor Board Fabrication & Assembly

For a sense of the full price, including tooling, NRE, stencils, etc., of getting the new sensor board fabricated and assembled professionally, a selection of totals from quotes obtained for this project are shown below.

Vendor\Quantity	**50**	**100**	**500**	**Selected Lead time**
Advanced Circuits	$1,140.00	$1,470.00	$4,055.00	5 weeks
Advanced Assembly	$1,897.03	$3,138.52	$7,727.04	25 days
Hughes Circuits	$3,501.50	$4,052.00	$8,780.00	15 days
Green Circuits	$1,682.95	$2,045.00	$3,968.00	4 weeks

References

[1] R. Dreslinski, M. Wieckowski, D. Blaauw, D. Sylvester, and T. Mudge, "Near-threshold computing: Reclaiming moore's law through energy efficient integrated circuits," vol. 98, no. 2, pp. 253–266.

[2] J. G. Koomey, "Worldwide electricity used in data centers," vol. 3, no. 3, p. 034008. [Online]. Available: http://stacks.iop.org/1748-9326/3/i=3/a=034008

[3] M. Pedram, "Energy-efficient datacenters," vol. 31, no. 10, pp. 1465–1484.

[4] J. Koomey, "Growth in data center electricity use 2005 to 2010." [Online]. Available: http://www.analyticspress.com/datacenters.html

[5] A. t. S. Energy, I. C. F. Incorporated, E. R. G. Incorporated, U. S. E. P. Agency, R. E. Brown, R. Brown, E. Masanet, B. Nordman, B. Tschudi, A. Shehabi, J. Stanley, J. Koomey, D. Sartor, P. Chan, J. Loper, S. Capana, B. Hedman, R. Duff, E. Haines, D. Sass, and A. Fanara, "Report to congress on server and data center energy efficiency: Public law 109-431." [Online]. Available: http://www.osti.gov/scitech/biblio/929723

[6] J. B. Marcinichen, J. A. Olivier, and J. R. Thome, "On-chip two-phase cooling of datacenters: Cooling system and energy recovery evaluation," vol. 41, pp. 36–51. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1359431111007058

[7] R. Subramanian, "Design of an instrumentation circuit for datacenter temperature measurements."

[8] P. de Groot, "Data center instrumentation project: Final report."

[9] K. Deland, J. Lenchner, J. Nelson, J. Connell, J. Thoensen, and J. O. Kephart, "A robot-in-residence for data center thermal monitoring and energy efficiency management." ACM Press, p. 381. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2070942.2071000

[10] Raritan. Data center environmental sensors | environmental monitoring. [Online]. Available: http://www.raritan.com/products/environmental-monitoring/environment-sensors

[11] Geist. Server & data center monitoring systems. [Online]. Available: http://www.geistglobal.com/products/monitor

[12] T.I. TMP175 | digital output | local temperature sensors | description & parametrics. [Online]. Available: http://www.ti.com/product/tmp175