Idaho Incubation Fund Program
Final Report Form

Proposal No. **IF15-004**
Name: **Dr. John Gardner**
Name of Institution: **Boise State University**
Project Title: **SAVE: Self-Organizing Air Vent System**

Information to be reported in your final report is as follows:

1. Provide a summary of overall project accomplishments to include goals/milestones met, any barriers encountered, and how the barriers were overcome:

<u>Electrical/firmware:</u>

<u>Hardware</u>

One of the most significant accomplishments from the state funding was the design, development and implementation of a wireless control module suitable for residential HVAC equipment. The SAVE board was designed as a low cost prototyping platform for developing the SAVE system. For wireless communication the board incorporates a 915 MHz radio controller and Xtapped loop Printed Circuit Board (PCB) antenna for long range, non-line-of-sight wireless communication. We verified distances of over 150 feet, a key metric for providing coverage across homes. To enable system debug and prototyping, all General Purpose Input Output (GPIO) pins were provided on breakout headers. Jumpers were provided for easily disabling and/or swapping out modules if necessary (for the radio and temperature/pressure sensor). Also included for debug were six Light Emitting Diodes (LEDs) and two tactile buttons for device interaction and state information. All components selected were done so with cost as a primary consideration.

The Freescale MPL3115A2 sensor was of particular interest because of its cost and dual pressure/temperature sensing capabilities. The trade-off was sacrificing a higher resolution (and much higher cost) pressure sensor that could more accurately detect the Heating, Ventilation, and Air Conditioning (HVAC) system state. The goal was to overcome this limitation through firmware by using "group intelligence" and more advanced algorithms. We were able to implement these techniques and the approach was able to successfully detect HVAC system states in the lab.

The SAVE board firmware enables up to 254 controlled zones, with each zone capable of controlling up to 254 automated vent registers. It utilizes a lightweight First-Come-First-Serve (FCFS) scheduler for running the system control. The radio control firmware is implemented as a simple ad-hoc mesh network that includes packet retry and checksum verification. The SAVE firmware also incorporates handling automated pairing between two devices, making the process much simpler for end users trying to configure the SAVE system.

<u>Software</u>

A HERC objective for the project was to reduce the liability of icing the HVAC coils during a cooling state. One step that was taken to reduce the likelihood of icing the coils was monitoring the number of closed vents in active zones. Adverse effects of closing too many registers in a forced air HVAC system were identified in a study completed at the Lawrence Berkeley National Laboratory[1]. The report recommended not closing more than 60% of the vent registers in a system as it would increase the chances of causing damage. To this end, the SAVE system now ensures that at least 50% of the vents are open for active zones to reduce the potential of icing the evaporator coils, which is a consequence of reduced airflow[2].

Another HERC object for the project was to improve the battery life. The SAVE firmware has taken a number of steps to improve power consumption. A low interval communication rate is used between devices to reduce power expended during radio broadcasts. The manual opening and closing of a vent was also moved to physical buttons on the board. This allows for the vent to go into a low power state as opposed to having to waste energy listening for an open or close event. Lastly, we began to explore the concept of implementing a vent "wear leveling" algorithm, where the system attempts to evenly distribute the number of opens and closes for each vent in a zone. This lets the SAVE system balance the power consumed by vents evenly across the network by choosing vents that have more power to open or close first.

Mechanical:

The initial test apparatus consisted of a hair dryer as the HVAC unit and plastic pipe as ductwork feeding the custom registers. This setup limited the ability to analyze the overall HVAC system to determine how SAVE would perform in real world applications. In order to collect data related to system health and energy use, a more robust testing prototype was developed (Figure 1).

Figure 1: A/C Testing Prototype

The prototype was built from a 12,000 BTU room air conditioner. Although smaller than a typical residential cooling unit, this portable version also uses the vapor-compression refrigeration cycle to provide cold air to the system. Since this unit contains an evaporator coil similar to those found in whole-house units, it could be used to explore system health and efficiency questions related to SAVE operation. In addition, custom supply and return ductwork were designed, fabricated, and attached to the air conditioner to simulate a

[1] Register Closing Effects on Forced Air Heating System Performance; http://epb.lbl.gov/publications/pdf/lbnl-54005.pdf

[2] Impact of evaporator coil airflow in residential air-conditioning systems: http://www.fsec.ucf.edu/en/publications/html/FSEC-PF-321-97/

small-scale residential HVAC unit. Two vent registers were installed on the supply side to simulate zones, and an actively controlled bypass damper was placed between the supply and return plena as is typical in zoned systems. Static pressure, temperature, in-duct air flow, total unit power, and fan current were measured using sensors.

Testing was completed by adjusting the two vent registers and bypass damper during cooling cycles. The results highlighted the importance of networked microcontrollers collecting and sharing data to control a zoned system. Simple open/close operation of registers based on temperature readings in rooms/zones does not account for the effects of back pressure and airflow restriction in the supply ducts. “On the fly” optimization adjustments are necessary to safeguard system health and attempt to make these adjustments in the most energy efficient way.

Typical residential HVAC units have design specifications that define air flow in the system as a function of static pressure differential across the evaporator coils. SAVE boards placed on both the supply and return sides can detect changes in this differential pressure when vent registers change position. With these controls, the SAVE network can make adjustments within the system to prevent reduced airflow. This prevents potential icing of evaporator coils due to reduced heat transfer, and undue strain on the blower fan caused by attempting to push air into pressurized ducts.

Both figures below show the static pressure increasing in the supply duct at steady state operation after the bypass damper and registers change state. Each configuration (with O=open and C=closed) describes the state of bypass damper, zone 1, and zone 2, in respective order.

Figure 2 demonstrates the extreme reduction in flow as more dampers are closed. Note the lower flow rate differences in central configurations: O<u>CO</u>/O<u>OC</u> and C<u>CO</u>/C<u>OC</u>. The minimal change in airflow in that part of the plot speaks to the importance of maintaining half of vents open. Closing the bypass results in a slight reduction, however, it is not nearly as extreme as the drop-off seen when both zones close.

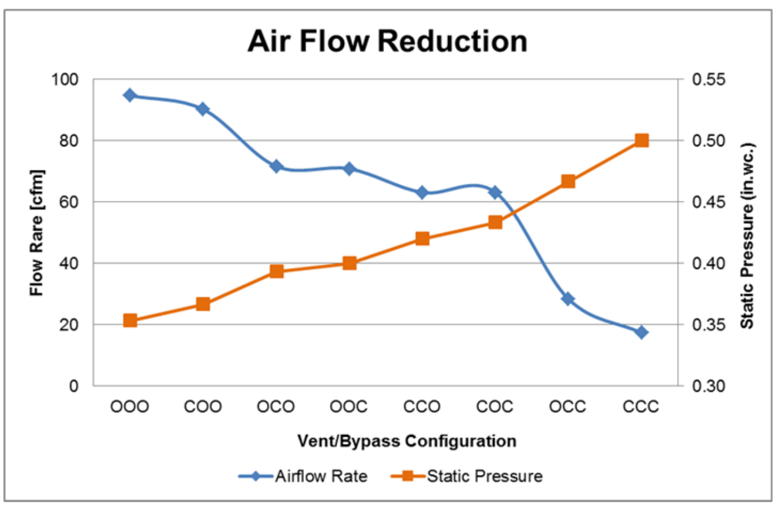

Figure 2: Relationship between flow rate and static pressure in the duct.

As the flow rate decreases due to increasing static pressure it must overcome, there are negative implications for the performance of the blower fan. Figure 3 is a fan curve that is typically provided by a manufacturer. The static pressure (SP) curve here is indicative of what was seen in the tests while closing vents: as pressure increases, flow decreases, and vice versa. In the figure, a vertical dotted line up to the flow and pressure (CFM, SP) coordinate passes through the brake horsepower curve (BHP). The horizontal dotted line to the right provides a value at that flow rate and static pressure reading. In short, as pressure increases (or flow decreases), power decreases.

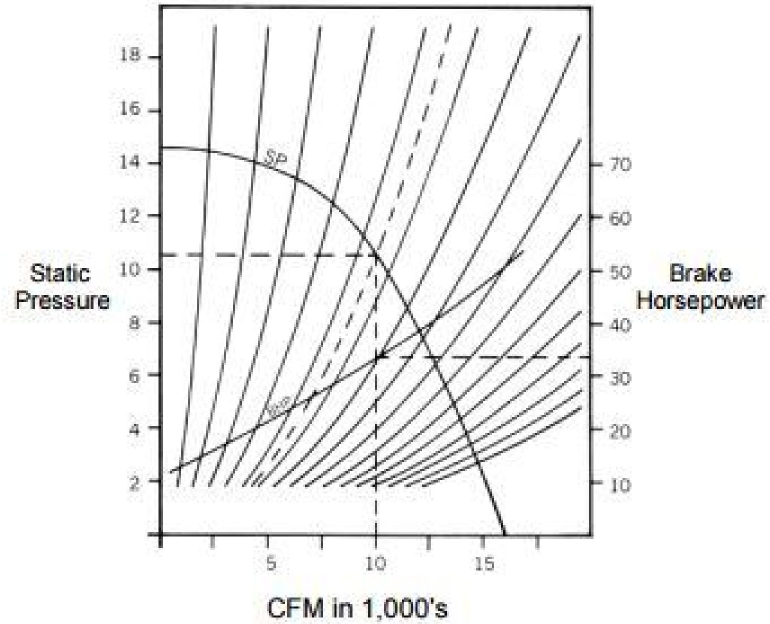

Figure 3: Typical Radial-Blade Fan Curve[3]

Figure 4 demonstrates this in our test configurations. Less power is often a desirable effect in a system. However, most fans are designed to operate in a certain "sweet spot" along the SP curve. Constantly moving along the curve reduces their efficiency. So whether the fan is using more or less power, the primary concern from a performance standpoint is how efficiently it operates. A second concern is that there are usually SP curve regions where a fan motor has the potential to stall, which would result in zero flow across the evaporator coils and possible equipment damage. Finally, a fan operating outside designed operating conditions will wear more quickly, resulting in increased maintenance or even early replacement costs.

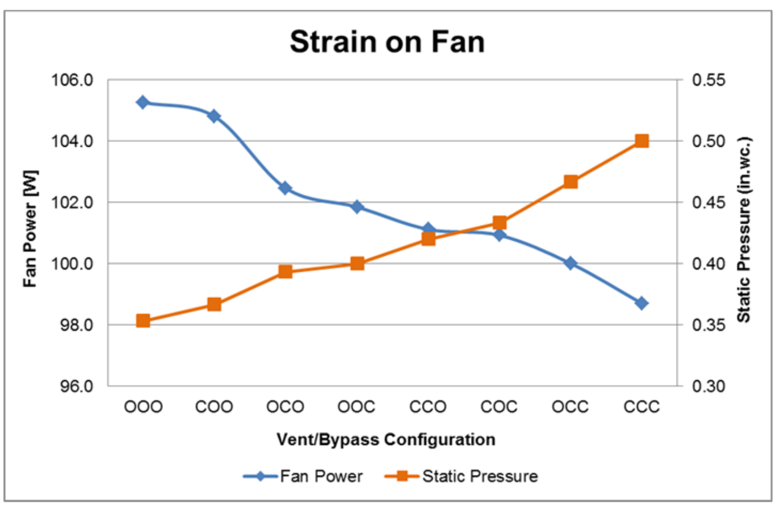

Figure 4: Relationship between fan power and static pressure in the duct.

Partially open bypass and registers

One additional area explored was the effect of partially open vents on static pressure and unit efficiency (EER). Figure 5 and Figure 6 demonstrate that there is minimal benefit to

[3] Understanding Fan Performance Curves: http://www.nyb.com/Catalog/Letters/EL-03.pdf

operating a system with partially open registers. Once open to 10%, pressure drop and efficiency essentially level off in relative terms. Based on these results, the team opted to focus on areas with more serious control over system health and efficiency to improve the SAVE system.

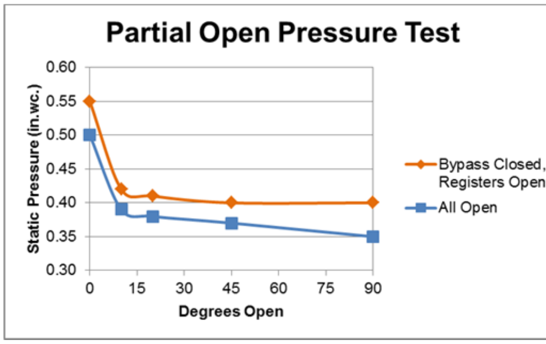

Figure 5: Static pressure as registers open.

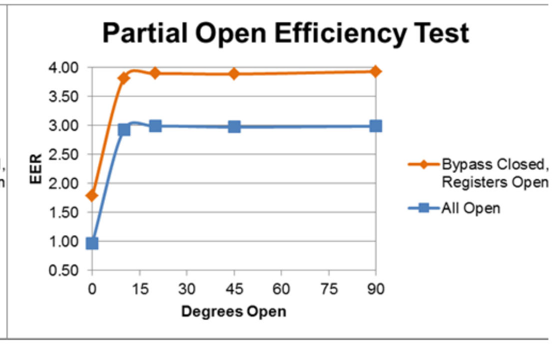

Figure 6: Unit efficiency as registers open.

Specific outcomes:

- SAVE board designed, fabricated, and debugged
- Software written and verified
- HVAC test bed constructed
- Tests performed to determine system performance and health

2. Describe the current state of the technology and related product/service:

Electrical/firmware:

Custom firmware has successfully been installed and debugged on the SAVE boards. A final iteration of the SAVE control algorithm detects the HVAC system state (on/off) to conserve power, controls the number of open vents to protect overall system health, and also assigns priority order to each zone/register for optimal temperature balance. The firmware scheduler and wireless protocol implementations were also updated to improve power consumption and increase system reliability. After a final round of testing on the HVAC prototype, it is ready for deployment in a more extensive testing environment.

Mechanical:

SAVE has outgrown the portable air conditioner prototype after testing system health and energy efficiency implications. However, the current setup can be used in the future for other types of HVAC testing. Another option for continued research is to modify the fan and compressor control systems to determine how more advanced controls can improve the unit's operation and efficiency.

3. List the number of faculty and student participants as a result of funding:

Faculty:	Dr. John Gardner (PI)
	Dr. Gang-Ryung Uh (Original PI)
Staff:	Kelly Moylan (Senior Research Associate)
	Kelley Dobelstein (Reseach Associate)
	Beau Husfloen (Research Engineer)

Students: Kyle Schwab (Graduate Research Assistant)

4. What are the potential economic benefits:

Zoned residential HVAC system benefits are traditionally split between providing greater comfort or being more energy efficient (i.e. reducing utility costs). A study completed by the National Association of Home Builders National Research Center explains this as “a simple zoning system can provide energy savings or increased comfort, but not necessarily both at the same time.”[4] Thus, in order to make a system like SAVE beneficial for homeowners more advanced methods must be implemented.

Networked controls communicating with one another throughout the system have the best potential to provide both comfort and efficiency while maintaining overall HVAC system health. There are detractors of simple open/close register “smart” controls. However, even some in that camp concede that well-executed algorithms have potential. Lloyd Alter, recognized with a Leadership Award in 2014 by the U.S. Green Building Council, is one of these detractors. In a recent article[5] he concedes that this type of product will eventually be able to communicate well enough to provide energy benefits without compromising the overall HVAC system.

SAVE has the potential to be this product. The system excels in communication between components. In its current state, the majority of communication happens between boards measuring temperature at individual registers, which are grouped into set zones but communicate independently. Static pressure sensors on the boards are also used to detect system states and open/close registers as the unit cycles on and off. Continued work on the SAVE software to include more sophisticated HVAC unit monitoring/controls as a part of the dynamic communication already in place has the potential to provide the solution Alter alluded to: improve comfort levels while saving energy and maintaining system integrity.

5. Description future plans for project continuation or expansion:

Based on recent research, several well-funded competitors have entered this gap in the market since the SAVE project launched. A few, notably Ecovent and KEEN Home, have large teams including executives with extensive startup business, finance, and technology experience. Considering these new market presences, the SAVE team does not see this system as a viable option to compete at this time. However, certain aspects of the project, including the mesh networking aspect of the communication algorithm and the mechanical testing apparatus, may be used for future research in other areas. In particular, the hardware and software architecture may be particularly well suited for introduction into ‘smart appliances’ which are capable of interacting with smart grid in a manner which is both beneficial to the overall grid stability and robust to disturbances.

6. Please provide a final expenditure report (attached) and include any comments here:

Dr. Gang-Ryung Uh, the initial PI for this project left Boise State University for a position in the private sector mid-year. Dr. John Gardner was selected to continue the research. Thus, participating personnel were different than initially proposed.

7. List invention disclosures, patent, copyright and PVP applications filed,

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[4] Mixed Performance Results for Zoned Cooling Systems: http://zonefirst.com/wp-content/uploads/2012/12/Mixed-Perf-Study.pdf

[5] Are Smart Vents Safe?: http://www.mnn.com/green-tech/gadgets-electronics/stories/are-smart-vents-safe

technology licenses/options signed, start-up businesses created, and industry involvement:

No intellectual property protections were attempted or completed. The industry partner for this project, FAMCO, was invited for a final demonstration and discussion of the SAVE system.

8. Any other pertinent information:

In addition to market saturation, another hurdle in monetizing the SAVE system was revealed in discussions with FAMCO personnel. As mentioned previously, in order to implement a system that is both safe and advantageous to customers more sophisticated controls should be used. However, this may result in a disconnect with target customers. According to FAMCO, a simple drop in set of registers is what an average do-it-yourself homeowner will be looking for on a Saturday afternoon. Installing the SAVE system as presented here would require a HVAC professional. If system installation goes beyond an afternoon project that can be done by a non-professional, those customers will be less willing to buy SAVE.

FINAL EXPENDITURE REPORT

A. FACULTY AND STAFF		
Name/Title	$ Amount Requested	Actual $ Spent
Kelly Dobelstein	$200	$200
John Gardner	$22,770	$20,645.24
Gang-Ryung Uh	$2,545	$2,344.92
Beau Husfloen	$3550	$7,440
Kelly Moylan	$2075	$1,970.64
B. VISITING PROFESSORS		
Name/Title	$ Amount Requested	Actual $ Spent
C. POST DOCTORAL ASSOCIATES/OTHER PROFESSIONALS		
Name/Title	$ Amount Requested	Actual $ Spent
D. GRADUATE/UNDERGRADUATE STUDENTS		
Name/Title	$ Amount Requested	Actual $ Spent
Kyle Schwab	$5580	$5,856.15
E. FRINGE BENEFITS		
Rate of Fringe (%)	$ Amount Requested	Actual $ Spent
Kelley Dobelstein	$18.34	$18.34
John Gardner	$7,058.70	$5,909.73
Beau Husfloen	$131.66	$527.71
Kelly Moylan	$684.75	$712.77
Kyle Schwab	$120.34	$71.35
Gang-Ryung Uh	$601.21	$601.21
PERSONNEL SUBTOTAL:	**$45,335**	**$46,298.06**
F. EQUIPMENT: (List each item with a cost in excess of $1000)		
Item/Description	$ Amount Requested	Actual $ Spent
1.		
2.		
EQUIPMENT SUBTOTAL:		$0.00
G. TRAVEL		
Description	$ Amount Requested	Actual $ Spent
1.		
2.		
3.		
TRAVEL SUBTOTAL:		

H. PARTICIPANT SUPPORT COSTS:

Description	$ Amount Requested	Actual $ Spent
1.		
2.		
3		
PARTICIPANT SUPPORT COSTS SUBTOTAL:		

I. OTHER DIRECT COSTS:

Description		$ Amount Requested	Actual $ Spent
1. AMAZON MKTPLACE PMTS SR509857b S Cordon 2 Rasberry Pi 2 Model b 1GB PC 6PRJ000379 TXN00160430			$139.98
2 WW GRAINGER AC items TXN00157391			$272.7
3. WW GRAINGER AC items TXN00157397			$906.05
4. WW GRAINGER AC equipment TXN00159761			$409.05
5. WW GRAINGER Materials for SAVE Air Vent Research Project per grant terms. TXN00168230			$148.33
6. 3D ROBOTICS INC Materials for SAVE Air Vent Research Project per grant terms. TXN00163663			$31.86
7. WW GRAINGER Materials for SAVE Air Vent Research Project per grant terms. TXN00160231			$100.09
8. ADAFRUIT INDUSTRIES Materials for SAVE Air Vent Research Project per grant terms. TXN00159313			$410.55
9. THE HOME DEPOT 1806 Materials for SAVE Air Vent Research Project per grant terms. TXN00159068			$75.58
10. WW GRAINGER Thermistor Probe Thermometer TXN00160614			$297.64
11. WW GRAINGER Materials for SAVE Air Vent Research Project per grant terms. TXN00160437			$368.09
12. WW GRAINGER Materials for SAVE Air Vent Research Project per grant terms. TXN00160416			$44.02
13.IN NINE DOT CONNECTS LLC purchased Altium software tool license for the 2nd year SAVE TXN00117723			$480
OTHER DIRECT COSTS SUBTOTAL:		$4,665	$3701.94
TOTAL COSTS (Add Subtotals):		$50,000	$50,000
TOTAL AMOUNT REQUESTED:			$50,000
TOTAL AMOUNT SPENT:			$50,000