Energy Research and Development Division

FINAL PROJECT REPORT

Low-cost Ultrasonic Anemoter for Use indoors and in HVAC Ducts Prototype Development and Testing

Gavin Newsom, Governor
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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities–Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company–were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Low-Cost Ultrasonic Anemometer for Use Indoors and in HVAC Ducts is the final report for the Anemometer project (Contract Number EPC-14-013) conducted by the Center for the Built Environment, representing the Regents of the University of California from the Berkeley campus. The information from this project contributes to Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the CEC at 916-327-1551.

ABSTRACT

Air systems that provide heating, cooling, and fresh air consume a third or more of the total energy used for heating, ventilation, and air-conditioning (HVAC) in commercial buildings. Much of this energy is wasted due to lack of accurate air flow measurement. Measurement uncertainty causes operators to maintain higher-than-necessary minimum flow rates that overcool and overheat buildings, as well as increasing the use of fan energy.

To reduce energy consumption in buildings, the project developed low cost anemometers (airflow sensors) to measure air flow. The team successfully developed and tested two different prototypes of the air flow sensors: an anemometer that measures air flow and direction in rooms, and an anemometer that measures the air flow within HVAC systems, such as ducts. The anemometers use Chirp Microsystems' tiny ultrasonic CH-101 sensors, which are disruptively inexpensive and sophisticated. A series of sound pulses is sent in both directions between each pair of sensors. The difference in the transit time, or time-of-flight, between each pulse determines the air flow velocity, and also its temperature. The research team tried several approaches to measuring the time-of-flight accurately and reliably. The current algorithm tracks the phase angle within a single defined wave cycle within the sonic pulse, using a simultaneous independent temperature measurement to keep its measurements within the wave cycle.

The current room anemometer measures air speeds from less than 0.05 meters per second (10 feet per minute) to a maximum speed of 7 meters per second (1400 feet per minute). It measures wind direction within an accuracy of ±5 degrees.

An application where the duct anemometer could greatly reduce energy consumption is measuring the airflow and temperature in variable air volume boxes and terminal units, especially directly downstream of reheat coils. Another application is in testing and balancing. The anemometer has potential to optimize cooling performance in data centers and controlling airborne diseases in hospitals.

Keywords: air flow, sensor, energy, HVAC, anemometer, VAV, variable air volume, commercial buildings

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EXECUTIVE SUMMARY

Introduction

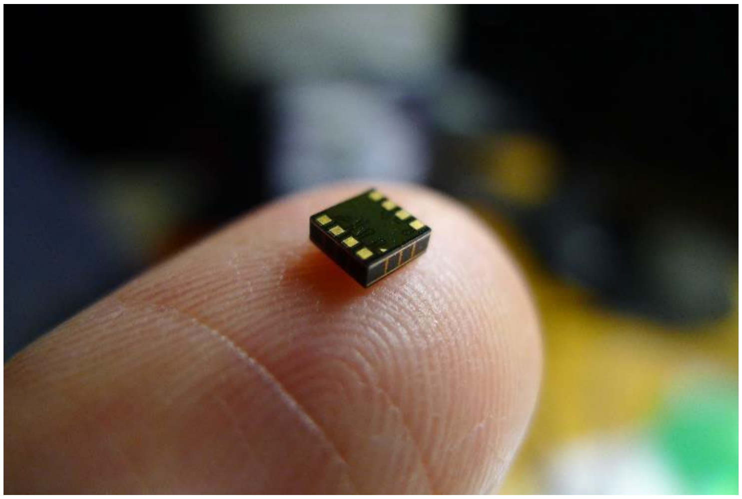
The heating, ventilation, and air conditioning (HVAC) systems in most office and commercial buildings do not operate optimally. Air speed and direction affect human comfort and productivity by maintaining a comfortably warm or cool environment, providing fresh air ventilation, and safety (such as isolating airborne diseases and exhausting harmful particulates). Most offices, labs, hospitals, and data centers in the United States use air systems for transferring warm or cool air or both, and providing air for ventilation. Airflow within rooms—important for environmental control in high-performing buildings and in labs, hospitals, and data centers—is almost never monitored because of the expense, power draw, directional sensitivity, and fragility of existing sensors. Air flow in HVAC ducts and inlets is currently obtained by pressure sensors, thermal, such as hotwire sensors, or inferred from damper positions. These methods are variously insensitive, subject to drift and fouling, expensive, and produce energy losses in the ventilation system.

The result is that building control systems do not maintain air flows accurately. Engineers and operators take this into account by using large safety factors for their minimum flow set points, often resulting in over-ventilation and over-cooling/heating at great energy cost. Sometimes because of efforts made to reduce energy bills, or mechanical problems like stuck dampers, indoor spaces do not receive adequate ventilation, resulting in poor indoor air quality, which reduce comfort and productivity, resulting in negative health effects. In 2016, air systems consumed about a third or more of the energy used in all commercial building HVAC, constituting 11 percent of California’s total energy. Improved and lower-cost methods for obtaining accurate and reliable air speed and air flow measurements have great potential for reducing wasted energy consumption and improving air quality.

Project Purpose and Approach

This project developed a new low-cost air-flow sensor, or anemometer, to identify the actual flow of air in rooms and air ducts. The Center for the Built Environment at University of California, Berkeley, led the research team, which included the Software Defined Buildings research group in its Computer Science department, and Chirp Microsystems. The approach used miniature ultrasonic devices (leveraging high-volume silicon manufacturing techniques for disruptively low cost) that were recently developed by Chirp Microsystem (Figure ES-1). The team configured these “transceivers” to transmit and receive ultrasonic signals, then use the transit time (or time-of-flight) of the sonic signals, to estimate air speed and direction. The team developed the hardware and firmware to orchestrate the timing of the signals, process the data, and transmit it to a server or local computer where algorithms and filter determine the measured air flow.

Figure ES-1: Miniature Ultrasonic Sensor



The heart of the disruptively low cost of these anemometers is the Chirp Microsystems CH-101 ultrasonic transceiver. It combines speaker, receiver, and processing to provide comprehensive output in digital form.

Photo Credit: Richie Pryzbyla, Chirp Microsystems

The researchers also designed the anemometer enclosures to minimize aerodynamic and acoustic interference, and amplify desired signal. The researchers produced a room anemometer for measuring indoor spaces such as rooms and data centers. They created two versions of a duct flow anemometer for measuring air volume and temperature passing through HVAC ducts and inlets.

Industry partners then took the anemometers and tested them in their facilities. Vigilent, a firm that provides sophisticated control of HVAC systems in data centers, tested the room anemometer. Price Industries, the world leader in manufacturing HVAC components, especially variable air volume systems, tested the room anemometer and provided a variable air volume component for lab testing. Big Ass Fans, manufacturer of efficient and smart ceiling fans, also tested the room anemometer. In addition, project partners Taylor Engineering and TRC worked with the team to identify applications and applicable standards for the use of these new low-cost anemometers.

Project Results

The research team successfully developed and tested prototypes of the room and duct anemometers. Both anemometers used arrangements of ultrasonic sensors that create a set of sound pathways among each pair of sensors and improve air movement monitoring.

The research team has also successfully developed and tested two air flow sensors: an anemometer that measures air flow and direction for rooms, and an anemometer that measures the air flow within HVAC ducts.

- Both anemometers use high-frequency ultrasonic transceivers arranged to create a set of sonic pathways. Pulse signals are sent in both directions down each path, and the differences in their times-of-flight determine the wind velocity along the path. The time-of-flight is measured by the phase angle of a defined wave cycle within the pulse. The method is guided by a coincident temperature measurement. The signal processing represents a unique innovation in acoustic anemometry.
- The anemometers include a built-in thermometer to supplement the sonic temperature measurements. They include a built-in 802.15.4 radio for wireless communication to a router/internet, and a built-in magnetic compass/tilt sensor to permit self-orientation relative to the earth’s horizon and zenith.

The research team consulted with HVAC controls engineers (Taylor Engineering, Vigilent, TRC) and manufacturers (Price Industries, Big Ass Fans) in brainstorming potential applications for the anemometers, then evaluating each potential application for cost and benefit. The potential applications include:

- Measuring variable air volume box and terminal unit airflow and average temperatures directly downstream of reheat coils. A new variable air volume box with these measurements embedded would not require the conventional flow restriction, and thus would have lower pressure drop (estimated to save 10 percent of the annual electricity cost. The ability to accurately detect low air speeds could result in less reheat and lower minimum air flows, which has been shown to substantially reduce common levels of HVAC energy use. A retrofit airflow sensor for variable air volume boxes could allow the HVAC unit to be turned down to a controllable minimum airspeed. This application was identified as perhaps the most innovative application of the ultrasonic anemometer.
- Accurately measuring the full flow of outside air, improving outside air control in buildings and decreasing associated measurement costs.
- Accurately and inexpensively measuring average air temperature and measuring temperature asymmetry in air handlers and ducts downstream of economizer mixing spaces, and heating or cooling coils. Flow sensing at variable air volume diffusers. The ultrasonic anemometer could increase the market of variable air volume diffusers.
- Testing and balancing. Typical HVAC specifications require that the test and balance contractor test airflow at all important parts of the system, including the air handler, variable air volume boxes, and diffusers; and often at multiple airflow setpoints. Using the ultrasonic anemometers has the potential to reduce the cost of some of this testing and balancing work.
- Corrosive environment applications. If the ultrasonic anemometer transceivers were protected by a weatherproof cover, it could open up other options for sensing in contaminated or corrosive environments:

    - Commercial kitchen ranges
    - Fume hoods
    - Hospital and laboratory room pressurization control

Technology Transfer

This project has laid the groundwork for further commercial development of the anemometer prototypes and further research in applying the anemometer in variable air volume boxes and ducts to save energy, especially in data centers and hospitals (which consume an enormous amount of energy using air systems), and other applications. The estimated cost of the anemometers (purchasing 10,000 at a time) is approximately $65 to $120 each (depending on the enclosure and number of sensors). Ths price is significantly lower than the current market price of flow probes with thermal dispersion sensors which are $1,000-$4,500. The material cost of a single flow cross with pressure sensor used in variable air volume boxes is $10 per sensor. The anemometers can use either wireless transmission or wired output for the data output. When battery powered for continuously monitoring applications, a 19-Amp-hour D-cell battery is expected to last 0.5 year to 10 years, depending on the selected sample interval rate.

The researchers met and visited with several potential manufacturers: Davis Instruments (potential for development of room anemometer for outdoor use), Swegon (potential for room anemometer in test facility and duct anemometer in their small round ducts for room-to-room balancing), Bayside HVAC as representative for Air Monitor (manufacturer of air flow sensors for handheld tools and ducts), and Price Industries (manufacture of large commercial HVAC systems), and sent materials to Krueger, Ruskin, and Ebtron. In 2020, the research team filed a provisional patent application.

Benefits to California

The anemometer technology can provide many benefits to California commercial and residential ratepayers, including lower costs of energy, greater reliability, increased safety, economic development, and environmental benefits.

The most promising application is in replacing flow sensors in HVAC flow stations, such as variable air volume boxes. Control systems can reduce fan speeds when measured airflow indicates ventilation requirements have been met, resulting in improved system operation, power reliability, and reduced grid impacts. Assuming a 15 percent final market penetration for new variable air volume applications, and a 10 percent penetration for retrofit variable air volume boxes, the estimated total statewide savings is 265 gigawatt-hours (GWh) per year (0.3 percent of estimated total commercial building electricity consumption in 2030) and 38 million therms per year (1 percent of estimated total commercial building natural gas consumption in 2030). The reduced energy equals $90 million per year in reduced energy bills for California building owners and occupants, and reduced operations and maintenance costs. Annual environmental benefits include an estimated savings of 226,000 metric tons of equivalent carbon dioxide. Safety of occupants is improved when ventilation air is accurately measured, because inaccurate pressure sensors often lead to reduced zone ventilation rates, and malfunctioning outside air dampers often do not provide sufficient minimum outside air. This project has provided work for 30 individuals in California for a total of 110,000 hours during 3.5 years. The mature technology has the potential to create high technology manufacturing jobs in California.

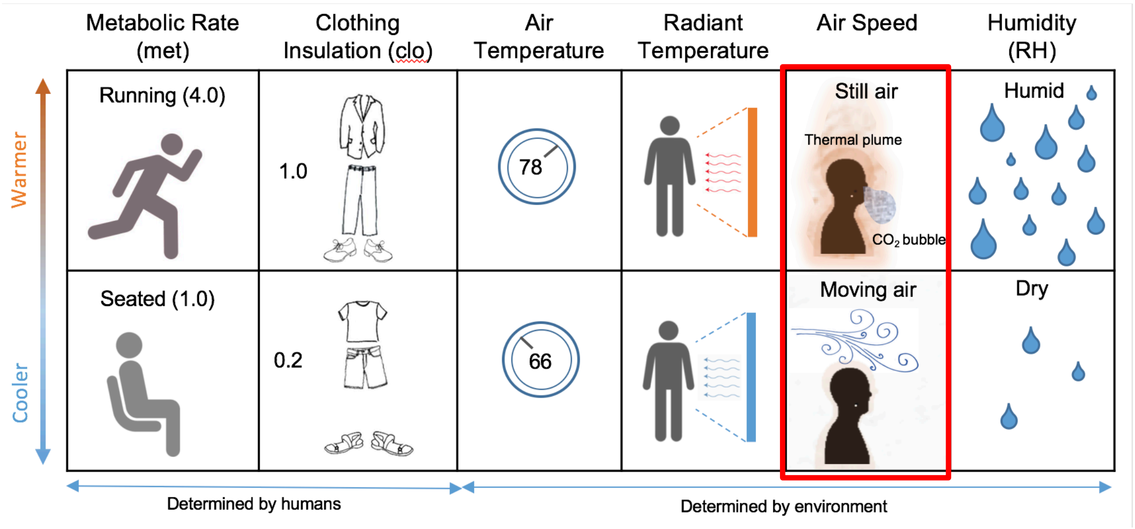
CHAPTER 1:
Introduction

Measuring Air Movement in Buildings

Thermal Comfort, Energy, and Safety

Air speed and its direction affect the indoor environment in numerous ways. They affect occupants' thermal comfort, their ventilation and the quality of the air they breathe, and their exposure to hazards like smoke in fires and pathogens in hospitals and laboratories. In addition, the air movement in buildings' HVAC systems has many energy consequences—both in the fan power used to produce the movement, and through the building thermal controls whose operation relies heavily on knowing the air movement. For the indoor thermal environment, four variables apply: air, radiant temperature, humidity, and air movement (Figure 1). Of these, air movement is the only one that cannot now be monitored easily or economically.

Figure 1: Thermal Comfort



Air speed is one of four environmental or physical parameters that affect thermal comfort.

Source: Therese Peffer

In the United States, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Standard 55: *Thermal Environmental Conditions for Human Occupancy* is the standard that guides the range of environmental conditions to achieve acceptable thermal comfort for building occupants.

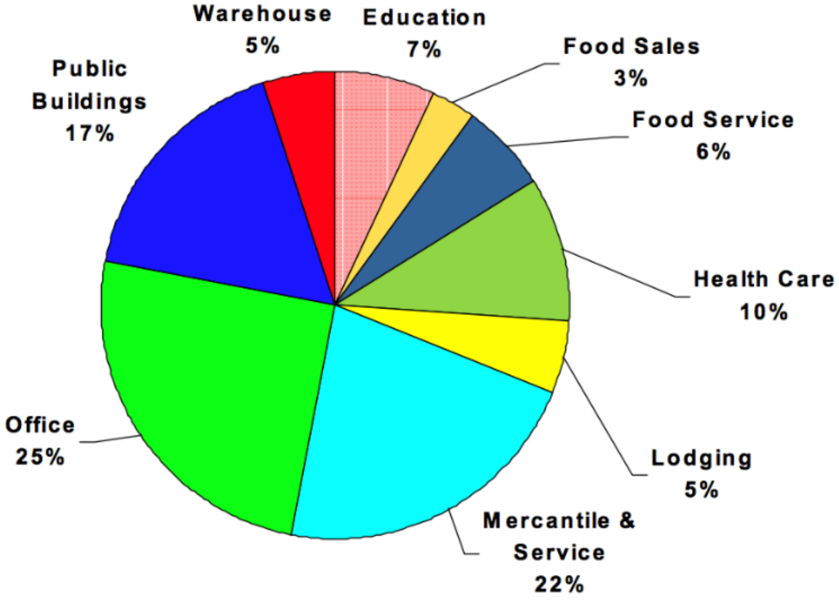
Standards such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Standard 62.1: *Ventilation for Acceptable Indoor Air Quality,* establish minimum fresh air requirements in buildings. Outside air must be introduced to replace indoor air at known rates. The flow through ducts, inlets, and exhausts must be measured to assure these rates. In addition, knowledge of the direction of polluted air flow is critical for many safety applications: controlling airborne diseases in hospitals, the flow of toxic gases in fume hoods, particulate matter in commercial kitchens, and the movement of smoke during fire emergencies.

For each of these environmental quality issues, monitoring of air flow and its direction has energy and environmental quality consequences.

Heating, Ventilating, and Cooling with Air

The HVAC systems in most offices, retail buildings, laboratories, hospitals, and data centers in the United States use air for transferring energy (Figure 2).

Figure 2: Types of Commercial Buildings That Use Air Systems



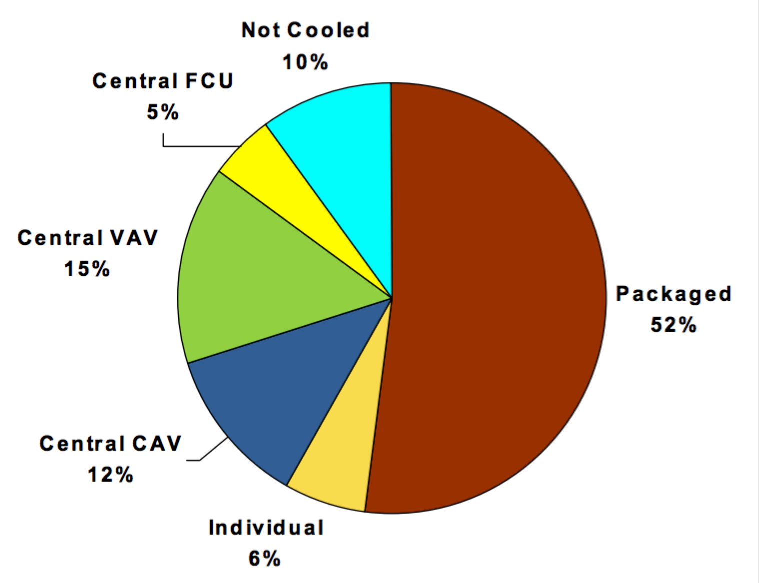
These types of commercial buildings have air HVAC systems.

Source: Westfalen et al, 1999, p. 1-2, Figure 1-3

Heated or cooled air (from a boiler, furnace, heat pump, or chiller) is distributed within the building through ducts, ad delivered to the room or zone via a grilled opening. The commonly used variable air volume (VAV) systems in commercial buildings use a metal box with a controlled damper for each zone that supplies a variable flow of air depending on the temperature or ventilation requirements of the zone. These boxes often have water or electrical reheat coils to adjust the temperature of the air supplied.

The energy that is required to distribute warmed or cooled air, to reject to the environment the heat discharged by cooling systems, and to move air for ventilation requirements is often called parasitic energy. Figure 3 shows a breakdown of the this energy in the HVAC systems commercial buildings. Using 1995 data, "parasitic energy use in commercial building HVAC systems accounts for about 1.5 quads [quadrillion British thermal units] of primary energy use annually, about 10 percent of commercial sector energy use, and about 20-60 percent of HVAC electricity use" (Westphalen et al, 1999, p. 1-1 and 2-1). The large range (20-60 percent) reflects the variety of air-based HVAC systems in buildings, and runtimes and efficiencies of various components. Reports from more recent papers indicate similar numbers: (Brelih, 2012) suggests that fans use 40 percent of all electricity in HVAC systems; a 2016 article in Automated Building suggests fans use 30 percent of total HVAC energy in typical commercial buildings (PlantPro, 2016), and guide from Australia describes on average about 34 percent of HVAC energy in commercial buildings is consumed by fans (Lecamwasam, Wilson, & Chokolich, 2012).

Figure 3: Types of Air-based HVAC Systems in Commercial Buildings



The majority of packaged systems reflect the large number of small commercial buildings.

Souce: Westfalen et al, 1999, p. 1-4, Figure 1-4

In 2016, commercial buildings consumed 18 percent of US primary energy, 18 quads out of US total 97.3 quads. California's commercial buildings used 1.477 quads (19 percent of California's 7.830 quads energy total).[1] According to the California Commercial End-Use Survey (CEUS) 2006, heating, ventilation, and air conditioning account for 1.6 percent, 11.9 percent, and 14.9 percent respectively of the total electricity use for California commercial buildings—28 percent total. Air-based systems in California commercial buildings include central VAV often found in office buildings, and packaged systems (such as Roof Top Units or RTUs) found on small commercial retail buildings. If claims regarding percentage of fan consumption are accurate (20-40

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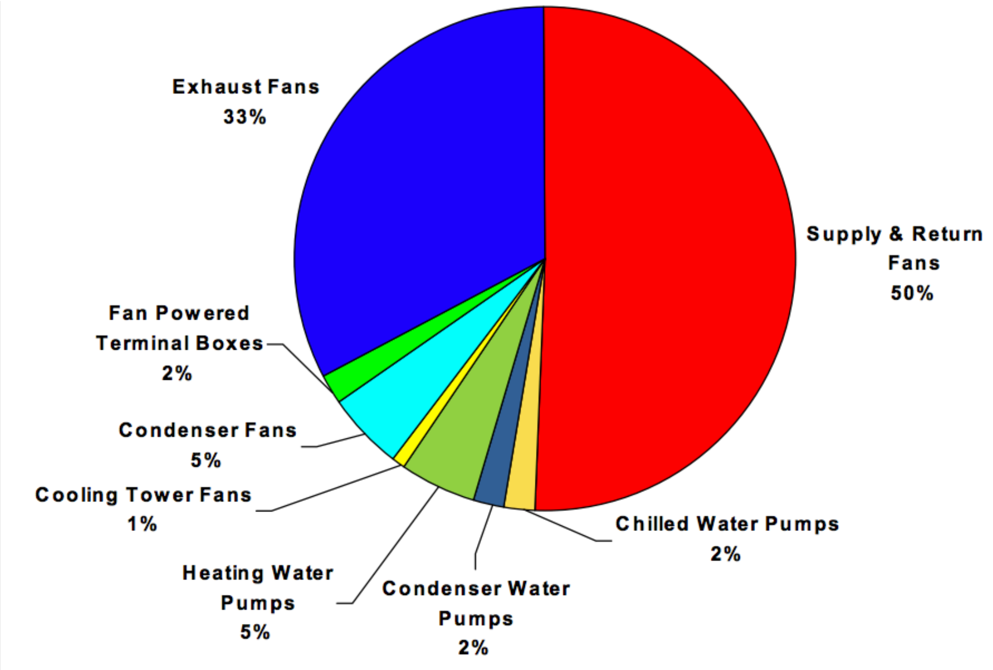
[1] https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_sum/html/sum_btu_1.html&sid=US

percent of the HVAC electricity), this amounts to somewhere between 6 and 11 percent of total California commercial electricity.

As shown in Figure 4, supply fans (including evaporator fans of packaged units and fan-coil unit fans) have high energy use because: "1) they are used in [all] system types, (2) air is an inherently inefficient heat transfer medium, (3) typical air distribution design practice involves considerable pressure drop for filtration, cooling and heating coils, terminal boxes, and diffusers, and (4) many of these fans operate at 100 percent power during all building occupied periods" (Westphalen et al, 1999, p. 1-2). Exhaust fans tend to also run constantly during building-occupied periods.

Figure 4: Types of Air-Based Equipment in Commercial Buildings



The equipment used to move and condition air in buildings consumes 10 percent of the total energy use in commercial buildings.

Source: Westphalen et al, 1999, p. 1-2, Figure 1-2

The Challenge of Measuring Air Movement in Buildings

The primary problem of measuring air movement in buildings in general is cost. Airflow within rooms—important for environmental control in high-performing buildings and labs, hospitals[2], and data centers—is almost never monitored because of the expense, power draw, directional sensitivity, and fragility of existing sensors.

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[2] The health care sector has high energy use intensity (energy use per square foot of floorspace) due to high ventilation rates, high cooling loads, and long hours of occupancy (Westphalen et al, 1999.

Air flow in ducts, and in other HVAC equipment such as air handling units, outside air measurement stations, variable air volume boxes, and diffusers, is currently obtained by damper position, pressure sensors, or hotwire sensors. However, airflow in ducts is hard to measure accurately because it is never uniform across the duct and is affected by surrounding conditions, such as elbows, fans, and boxes, which introduce turbulence. Figure 5 shows an example of the configuration of the airflow sensors that must be positioned in a duct constriction, upwind of the variable air volume box inlet.

Pressure-drop-based sensing using damper and orifice constrictions requires additional central fan power to drive air through the constriction; this type of sensing also loses accuracy at low flows, which are important for maintaining minimum ventilation requirements. Other types of pressure and hotwire sensors go out of calibration due to fouling, drift, and incorrect commissioning. The result is that building control systems cannot predict air flows accurately.

Poor airflow prediction causes designers and operators to use larger safety factors in their minimum flow set points, causing widespread over-ventilation and over-cooling/heating. In the field it is not uncommon to find outside air dampers sealed shut as operators attempt to mitigate over-ventilation[3]. Through these measures or through failures in the building system (such as stuck dampers, faulty valves), buildings can also show under-ventilation, which can cause indoor air quality issues. Direct flow measurement in ducts, fume hoods, and the occupied space would enable more responsive system control, and more immediate safety alarms should airflows be reversed.

In both cases—in rooms and in ducts—the labor to install wired airflow measurement systems may be cost-prohibitive. Therefore, it may be beneficial to make the monitoring point battery-operated and with wireless communication to the control system.

Air Movement Measurement

Air movement or motion are the general terms encompassing both velocity and speed (distance traveled by air in a period of time) and volumetric flow rate (volume of passing air in a period of time). Here velocity and speed are described in terms of measurements and applications in an unconstrained space, such as the occupied zone of the building. Then described is the volumetric flow measurements in terms of flow in a duct, inlet/outlet, or VAV box.

Air Velocity and Air Speed Measurement in Rooms

Air speed refers only to the magnitude of the air movement (a scalar quantity). It is the same as the air velocity along the direction of travel, but its direction is not defined. Speed can be obtained from velocity, but not the reverse. Air velocity is air movement traveling in a defined direction (a vector). Vectored air movement helps determine in

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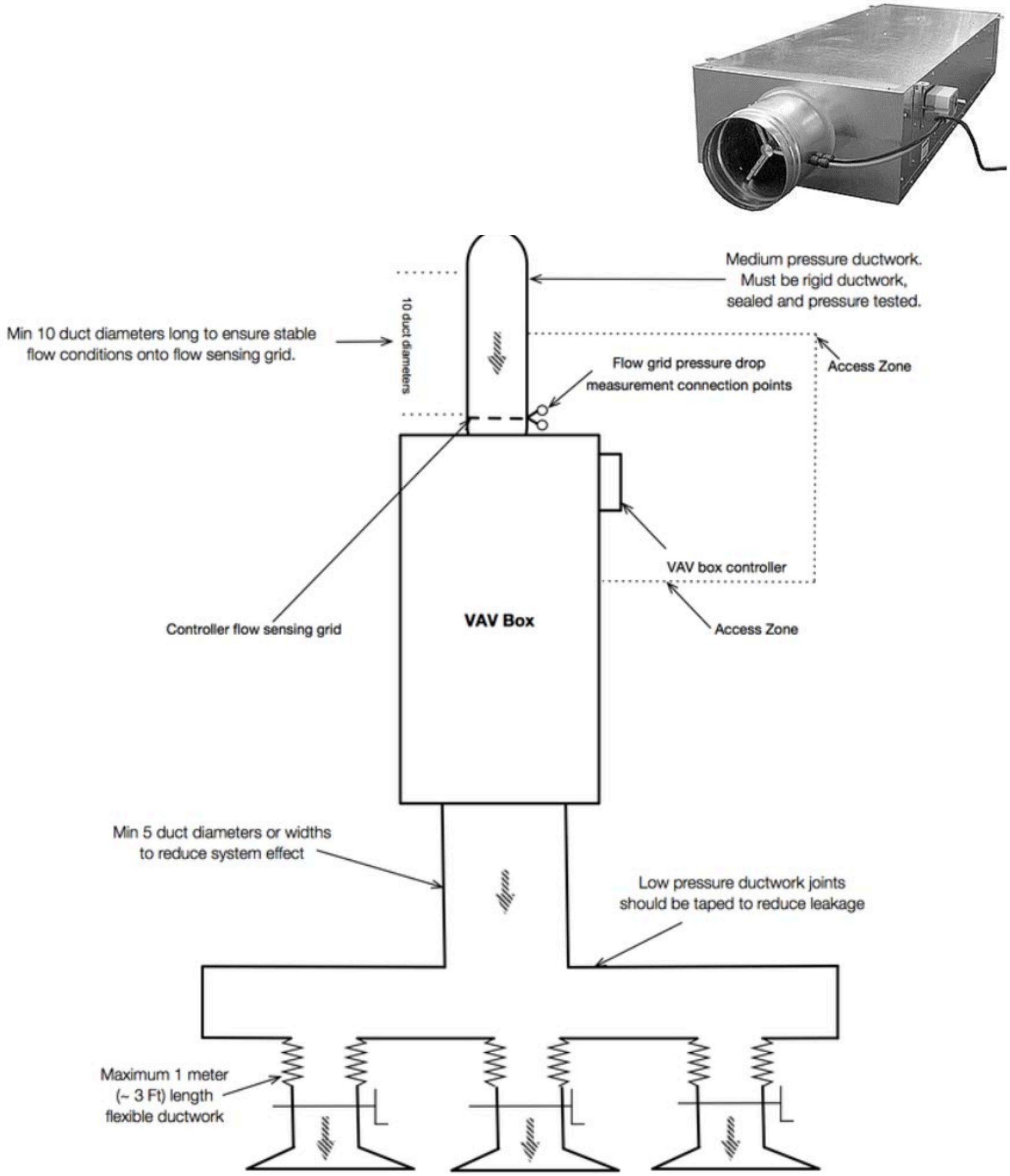
[3] Email communication, David Heinzerling, Taylor Engineering, March 2019.

what direction and how fast heat, ventilation, or pollutants/smoke are being transported.

Figure 5: Typical Pressure-Sensing Control of a Variable Air Volume Damper



The photo (upper right) shows the constriction (small round duct) to create a pressure drop for the pressure sensors before the VAV box. The diagram shows the proper configuration of the ducts into and out of a variable air volume box.

Source: https://bldwhisperer.com/vav-box-sensitive-install-as-follows/

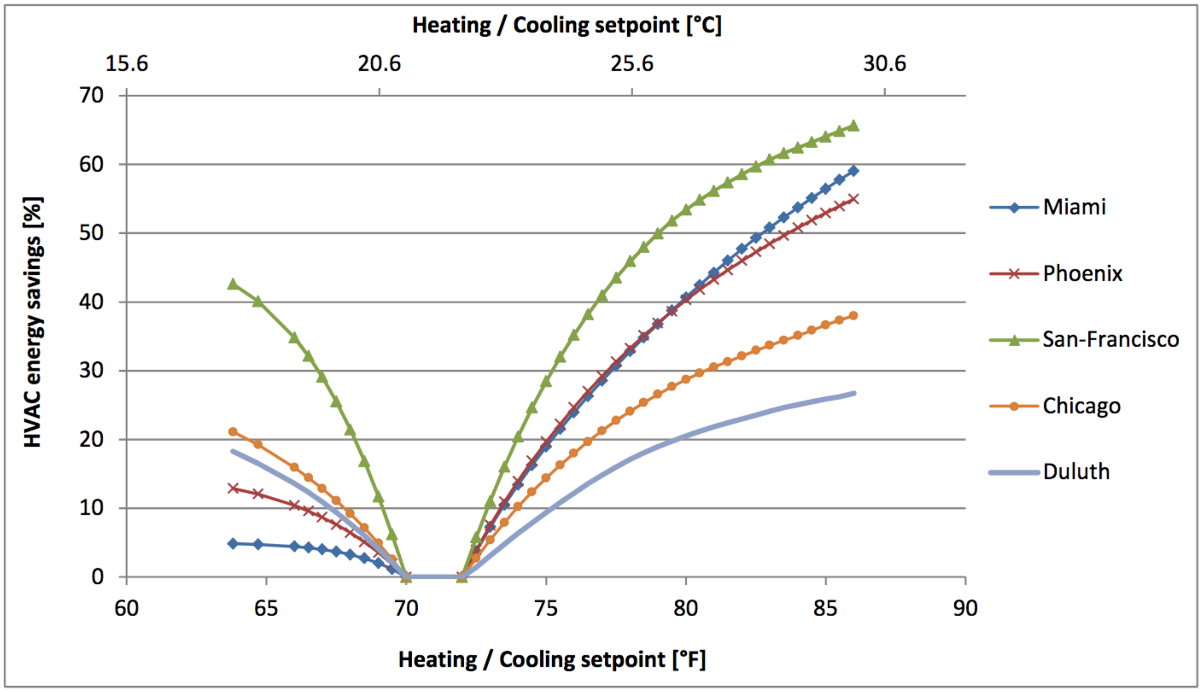
Applications of Room Air Speed for Cooling the Occupant

Air speed is used for the evaluation of human thermal comfort and physiological heat stress. Comfort and heat stress are determined by the rate at which heat is convectively transferred from the human body, and this heat transfer is largely insensitive to the orientation of the person relative to the wind. Since direction is unimportant, air speed is physically measured using spherical hotwire anemometers whose output is equal for all directions (or omnidirectional).

Air speed is important because it amplifies cooling in all but extremely hot temperatures. In cool temperatures, air speed needs to be low to minimize heat loss. Previous research provides the background to use air movement to appropriately cool occupants.

- Increasing air speed increases both sensible (dry) and evaporative heat loss from the skin.
- In cool conditions, air speed may cause excessive cooling, and occupants may perceive an unpleasant draft. When a building is heated, the temperatures should be at the lower end of the comfort zone (for example, 68°F to 72°F [20°C to 22.2°C]), and the air speed should not exceed 0.2 meters per second (m/s) according to American Society of Heating, Air-Conditioning, and Refrigerating Engineers, Standard 55. At these cooler temperatures, people are sensitive to air speeds down to 0.05 m/s (10 feet per minute[fpm]).
- Air speed is perceived as pleasant when a person is warm.
- Air speed over the skin should be at its practical maximum before the air conditioner comes on, and remain at maximum any time the air conditioner is on.
- Using air movement through ceiling fans or other personal fans, and raising the target temperature to 78°F (25.6°C) can easily provide 18 to 48 percent HVAC energy savings (Figure 6).
- Conductive cooling (that is, directly through a cooled surface) of the body to cool surfaces is not comfortable over time (possible exceptions are forearms and wrists). Thus, convective cooling by air is the key mechanism for personal cooling in buildings.
- Air speed improves air quality by reducing high carbon dioxide concentration levels near occupants, and improves occupants' perceived air quality (Ghahramani et al, 2018; Arens et. al., 2008).
- Air speed is especially effective for cooling people at higher activity levels, such as in sport facilities. Raising the setpoint of the indoor temperature can save HVAC energy.

Figure 6: Energy Savings From Expanding Temperature Setpoints



The right side of this graph shows simulated energy savings from increasing the cooling target temperature (or setpoint) of the HVAC system in different cities in the United States.

Source: Figure 3.5 in (Hoyt et al, 2014)

For evaluating comfort effects of air movement, such as from ceiling fans or operable windows and vents, sensors must be positioned close to occupants, such as on their desktops, or suspended in the space near them. For this to be practical, they must be small and standalone, ideally without wires for power or communications, and physically robust and inexpensive. The positioning is relaxed somewhat for controlling fans, automated window-opening mechanisms, and vent flows, since their estimated effects on comfort can be calibrated.

Applications of Air Velocity with Direction

Air velocity measurement may not be needed for comfort control, but is valuable in health, safety, and industrial process applications. Sensing the vector of airflows in hospital corridors, cleanrooms, or in data centers is important to ensure that airborne pathogens and particulates are controlled. Direction is valuable for fire/smoke monitoring as well. For accuracy, the sensors must be suspended in the airflow at some distance from the walls, ceiling, and floor to avoid boundary layer effects[4]. This again requires small sensors, to avoid interference with the activities going on in the space.

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[4] Immediately adjacent to windows, walls, floors, and ceilings is a thin air film, or boundary layer, that acts as a drag on adjacent air flows.

Current State-of-the-Art Air Speed Sensors

How are airspeed and air velocity now measured, in general and specifically within buildings? The state of the shelf (what is available right now off-the-shelf) in anemometry are:

1) Hot-wire and hot-film heated elements that measure the changes in current or voltage from airflow cooling.
2) Impellers such as propellers or rotating cups.
3) Eddy-shedding shapes where the frequency of cooling rate on the backside is sensed.
4) Devices that measure the difference between dynamic (velocity) pressure and static pressure, such as pitot tubes.
5) Ultrasonic anemometers, used in research or outdoors.

Most of these devices are limited by their directionality, requiring a rotating or gimbal support if they are to measure airflows in all directions. They also are limited in their accuracy. Readings in all but the ultrasonic anemometers will drift as sensors become dirty or corrode. Because they require sensitive moving parts or lightweight heating elements, they are fragile. The heated sensors in groups 1 and 3 require substantial electrical energy, preventing long-term operation without a power supply. All air flow sensors are expensive relative to sensors used to measure temperature, humidity, surface temperature, and light.

Air Flow Measurement (In Ducts, Inlets, and Exhausts)

Air flow refers to movement of a defined volume of air in a period of time. The unit of air flow is volume over time (t) [that is, cubic feet per minute]. Air flows are important because of energy, health (ventilation), and safety (smoke, fumes) concerns. The energy transported in ventilation systems (Q) is proportional to air flow (AF):

$Q/t = (AF) \times \Delta T.$

As mentioned above, parasitic energy is required to pump air against friction through duct systems with conventional pressure drops. Fan energy is an important part of total HVAC energy, on the order of 30 percent depending on system type.

Applications of Air Flow Volume in Ducts for Measuring Energy and Ventilation Rate

Air velocity and air speed sensors can be used to measure flows in ducts. If the velocity sensors are mounted in an array that samples the cross section of the duct—or if the velocity sensor is moved across the duct in a one-time calibration—the average of the measurements in the traverse can then be correlated to a single measurement point in the duct. This method is quite inconvenient. A sensor specifically designed to measure flow across the width of the duct would improve this method.

Since ventilation systems transport fresh air as well as heating and cooling energy, the ability to confidently maintain the minimum airflow to achieve required ventilation levels is critical. Without reliable airflow monitoring, this minimum is traditionally provided in variable air volume systems by a conservative fixed flow setpoint. This provides a higher air flow than required, which increases the building's total HVAC energy requirement an average of 30 percent over buildings that are under ventilation control that reliably maintains a ventilation minimum. Supplying just the minimum airflow through better ventilation control also reduces summer overcooling discomfort an average of 50 percent (Hoyt et al., 2014; Arens et al., 2011).

Where is the air going? A complete accounting of duct flows is normally not measured and is unknown. Losses from duct air leakage is known to be extensive (25 percent of total flow in some cases); dampers are often misadjusted or stuck, with unknown consequences.

The consequences of incorrect variable air volume setpoints are not currently detected by the building operator. Also, as filters load up with dirt, the airflow is reduced, but this is not observed in detail by the operator.

The above flaws with ductwork and dampers may affect the minimum ventilation supplied, and cannot be detected without feedback from airflow sensors.

Current State-of-the-Art Air Flow Sensors

The state of the shelf includes: hotwire arrays, eddy-shedding arrays, impeller arrays, pressure drop across an orifice plate, and pitot tubes. Flow hoods and duct blasters are used for research and commissioning. Tracer gas sensing is used for research and commissioning. As mentioned previously, incurring a pressure drop across a duct or variable air volume box to measure its flow results in a large fan power penalty. Fouling over time is a major problem with pitot tubes, hotwires, and impellers. Installation and maintenance is complex, and the cost is high. Currently these difficulties have led to a lack of sensing in ducts.

In addition, airflow in ducts is hard to measure accurately because the airflow is never uniform within the duct. Friction with the walls produces boundary layers with reduced flows. Changes in duct direction and cross section cause non-uniform local velocities within the duct cross-section. Integrating airflow and temperature in non-uniform cross-sections is currently very difficult: near elbows, in outside air measurement stations, in air-handling units, variable air volume boxes, and in laboratory flow hoods. Building commissioning and permanent control applications could benefit by improved duct flow sensors.

Current State of Ultrasonic Anemometers

First developed in the 1950s, ultrasonic anemometers use sound waves to measure air speed. Typically, the time-of-flight of sonic pulses are measured between two or three pairs of transducers. Commercially available[5] ultrasonic air speed sensors are shown in Figure 7. They are generally intended for outdoor use, where there is less requirement for accuracy at low speeds than indoors. The examples measure two-dimensional airspeed in a horizontal plane (WindSonic and WindObserver; using four transducers) and in three dimensions (WindMaster; six transducers).

Figure 7: Ultrasonic Anemometers

These ultrasonic anemometers are typically for outdoor use, and are not accurate at low air flows.

Source: http://gillinstruments.com/products/anemometer/anemometer.htm

Existing commercial ultrasonic three-dimensional anemometers use six transceivers for measuring three-dimensional flow, generally having three orthogonal paths between fixed pairs of transducers. The signals are sent and received in a single-pitch, single-catch arrangement. Such designs are not optimal because there is no redundancy should one of the sonic pathways be corrupted, such as in airstream blockage caused by the anemometer support structure. One or more of the xyz components of the air speed vector would be lost, and needs to be corrected for empirically.

A duct-airflow-monitoring station incorporating an ultrasonic anemometer has recently come on the market (Ultralink from Lindab).[6] This product is generating interest in the industry. It uses a pair of sensors measuring diagonally across a circular cross section. The hardware involved is inherently expensive. The system cannot detect differences between flow rates in different parts of the duct cross-section. The reported performance shows low accuracy at low speeds, but good performance across a wide speed range.

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[5] Homemade versions have also been published, such as: https://soldernerd.com/arduino-ultrasonic-anemometer/.

[6] http://www.lindab.com/global/pro/Pages/ultralink-next.aspx

Goals of the Project

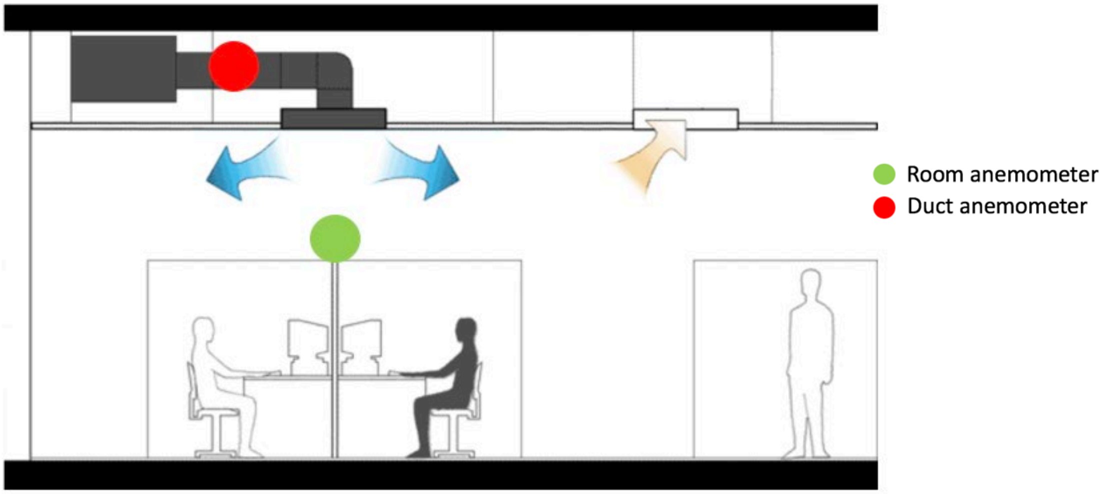
The first project goal is to develop two low-cost, low-power, accurate, calibration-free, and compact wireless airflow sensors for measuring:

- Air velocities and speeds in rooms, such as offices, data centers, hospitals, labs, and clean rooms.
- Volumetric air flow in HVAC ducts, air handlers, fume hoods.

The anemometers are to measure real-time air speed down to 0.05 (m/s), which is a very low value, but valuable for indoor applications. They are to operate and communicate using very low power, so that they can wirelessly monitor spaces and systems for long periods. They are to be durable, calibration-free, and inexpensive, for ready use in operation as well as commissioning buildings. They are also to measure real-time air temperature.

The second goal is to identify buildings applications (Figure 8) that would benefit from this new enhanced anemometry, and then prepare and publish design data, performance specifications, and generic control sequences for the most relevant applications. The energy/comfort/health benefits conferred by the new anemometers with their communications and controls would then be estimated through laboratory and field testing of prototypes by this project team and its industry collaborators. Such documentation would serve to jump-start the market for anemometer manufacturers. The project team intends to target its important findings to the standards committees controlling energy and environment in buildings.

Figure 8: Potential Location of Ultrasonic Anemometers



The duct anemometer would likely be located downstream of the variable air volume box (red circle). The room anemometer could hang from the ceiling or mount atop partitions (green circle).

Source: Center for the Built Environment

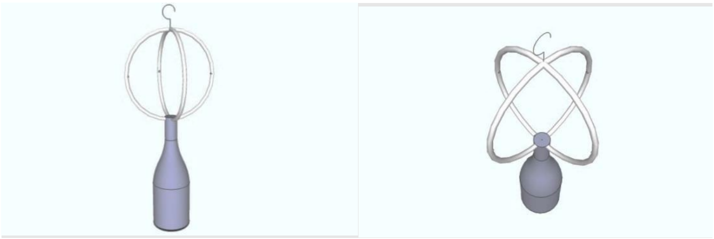
Project Approach

The research approach used ultrasonic speakers/microphones made using micro-electromechanical systems manufacturing techniques, first developed by Chirp Microsystems in 2014 for a different application (three-dimensional range finding). Such devices are integrated with processors as single chips on silicon wafers, leveraging semiconductor manufacturing techniques, creating a breakthrough for low-cost manufacturing. Initial applications were in range-finding, especially in gaming systems to detect and track motion, but they could also be applied to measuring air movement. Accurately measuring the time-of-flight of the ultrasonic pulses across a distance in both downwind and upwind directions provides very accurate measurements of wind speed and air temperature.

The transceivers are configured into two prototypes. In the “room” version of the anemometer, pairs of sensors capture the three-axis wind velocity vector. In the “duct” version, the multiple sonic paths across the duct cross-section allow the average volumetric airflow and its temperature to be assessed, even in highly non-uniform flows.

The room air velocity anemometer (Figure 9) uses an array of transceivers to measure the direction and the three-dimensional components of air movement. It can also be used as an omnidirectional air speed sensor. It can be suspended on a string from the ceiling and will orient itself magnetically. It can also be unobtrusively mounted on a pedestal extending from workstation surfaces like desktops or partitions. It should operate standalone for a year on a battery.

Figure 2: Initial Proposal for the Room Ultrasonic Anemometer Prototype



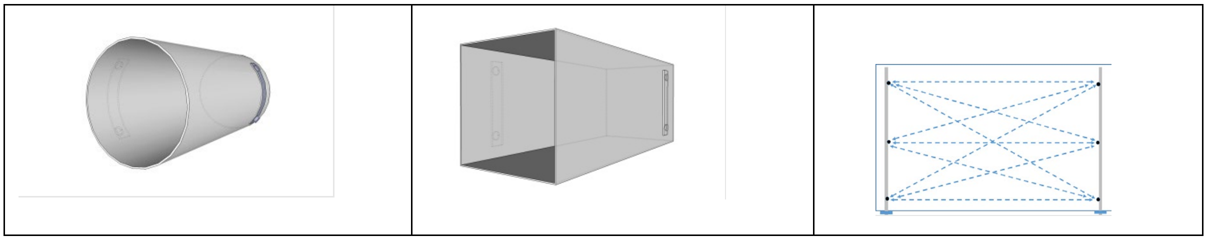
Within-room anemometer: Three-axis airflows, self-orienting, wireless. Ultrasonic transducers positioned in small holes in the rings. Ring diameter is 3 inches (75mm).

Photo Credit: Francisco Peralta and Ed Arens

During this project, there was a continuing technological breakthrough in the processing power, wireless communications, and power management capabilities of modern processors. These are used to provide a robust device that has the ability to communicate through the internet within buildings and mechanical systems for a year operating on a battery. The transceivers include an application-specific integrated circuit that provides digital data as well as sensing and controlling the ultrasonic sensor. They connect to a “carrier board” developed by the research team that orchestrates the timing of the transmission and reception of the ultrasonic sound pulse. The carrier board also contains a microprocessor and radio that sends initial processed data either to a server via a wireless router or to a laptop through a wired USB connection. The server or a laptop may perform the signal processing—the filters and mathematical machinations—to transform the time-of-flight measurements into an airspeed and direction.

The duct air flow version (Figure 10) is simply a differently configured arrangement of the same transceivers and carrier board. In this case, each of the transceivers on one side communicates at the same time to all the transceivers on the other side. Therefore, it averages the non-uniform airflows across nine pathways across a duct or orifice, allowing accurate measurement of volumetric flows in rectangular and circular ducts without requiring calibration, and with minimal insertion into the airstream (useful for dirty and corrosive airstreams found in laboratory exhaust and industrial processes). The design of the support structure and a way of easily inserting it into existing ducts is a key component of the project.

Figure 3: Concept of the Duct Ultrasonic Anemometer Prototype



Duct-airflow anemometer wands, as attached to sides of round and rectangular ducts. Multiple signal paths (3x3 array shown) across duct cross-section integrates non-uniform flows. Also measures flow temperature. (Wireless and connecting wire not shown).

Source: Francisco Peralta and Ed Arens

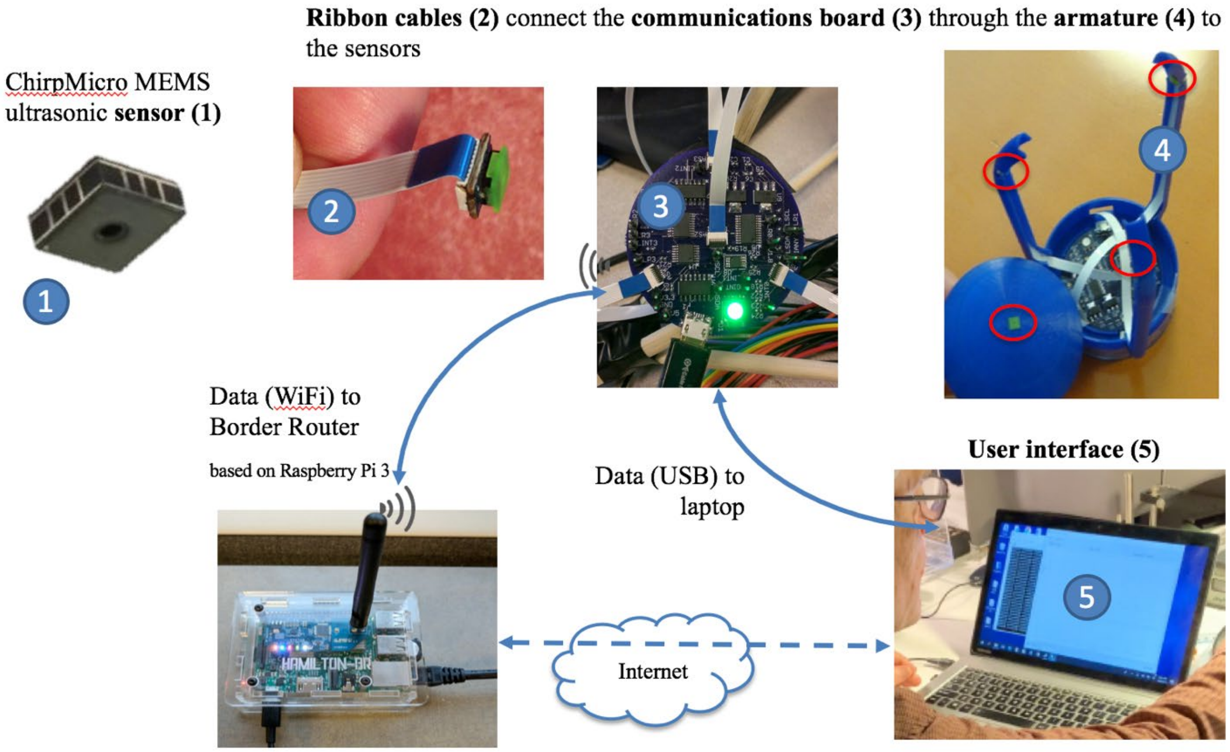
As with the room air velocity anemometer, the duct air flow can communicate wirelessly to a router and the internet, or via a USB connection directly to the user’s computer.

The remaining chapters describe the development of the anemometers, testing the prototypes in the lab, developing signal processing, filtering, and algorithms to convert the signals into velocity, calibrating the prototypes, and results from the industry partners field-evaluating the prototypes.

The hardware consists of the miniature ultrasonic sensors (Figure 11) that are connected by ribbon cable to a carrier board (which initiates and manages the timing of the sensors) that sends the data either through a wireless or wired transmission to a user interface.

Chapter 2 outlines the anemometer design: the configuration and aerodynamics of the transceivers into a room air velocity anemometer (four ultrasonic transceivers) and a duct air flow anemometer (four or six transceivers). Chapter 3 describes the processing of the data to form the air flow measurement and the user interface developed to view the data. Chapter 4 describes the potential applications, and Chapter 5 describes the production of select components of the anemometers for market. Chapter 6 is a discussion of the anemometer prototype design progression, potential energy savings, and next steps. Chapter 7 provides the conclusion. Appendix A contains the underlying technology: ultrasonic transceivers, anemometer calculations in converting times-of-flight into speed and direction (minimizing wake effects and filtering), the orchestration of the measurement process and hardware of the carrier board, and the communication of the data out (either by a mini-USB cable or the wireless signal). Appendix B defines the laboratory and field testing of both prototypes. Appendix C discusses recommended standard activities. Appendix D provides copies of three technical papers, and Appendix E provides user instruction.

Figure 4: Overview of the Ultrasonic Anemometer Prototype



The 3.5 mm-square ultrasonic sensors (1) are arranged in a 3-D (room) or 2-D (duct) array, with ribbon cables (2) attaching them to the carrier and communication board (3) and to the sensors (red circles) held by the vertical armature (4), which relays the data either through wireless or wired transmission to visualize the data in a user interface (5).

Source: Richard J. Przybyla, Ed Arens, Hui Zhang, Michael Andersen, Therese Peffer

CHAPTER 2:
Anemometer Design

This chapter describes the configuration of transceivers, aerodynamic design, reflection elimination, and support structure for the room anemometer and for the duct anemometer.

Room Anemometer

Early in the project, the researchers realized that if all Chirp Microsystems transceivers could transmit and receive the ultrasonic pulse at the same time, three pairs of sensors were not needed to achieve a three-dimensional reading; the minimum number of transducers needed was four arranged in a tetrahedron. In addition to reducing the number of sensors, this approach increases the number of velocity pathways from three to six. This allows three-dimensional velocity to be calculated with redundancy, which can be used to detect and correct errors introduced by the aerodynamic wakes from the support structure.

Figure 12 shows the initial prototype design concept.

Figure 5: Initial Concept of Room Anemometer in Tetrahedron Form

The struts hold the four transducers arranged in a tetrahedron shape. The connectors between each transducer and the carrier board are concealed in the base. The light blue lines show the transmit/receive pathways between the pairs of sensors.

Source: Francisco Peralta and Ed Arens, University of California, Berkeley

The physical design changed as the Chirp Microsystems sensor evolved. The transceiver now integrally incorporates a connector to an eight-lead ribbon cable. Their dimensions are accommodated in the support struts of the anemometer, which were printed on a three-dimensional printer and other plastics on campus (Jacobs Hall, University of California, Berkeley). In a series of prototypes, the support struts were widened. Figure 13 shows an early version that snapped together to allow easy assembly and disassembly of the ribbon cable and transceivers within the struts.

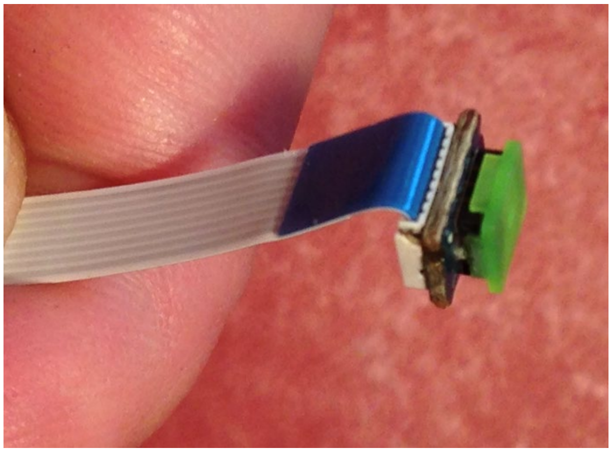
Figure 6: First Room Anemometer 4-Channel Tetrahedron Prototype

Left: the 3-D printed support system for the first room anemometer prototype, with sensors embedded in the vertical support arms. Right: an exploded view SolidWorks rendering of support system.

Source: Francisco Peralta and Ed Arens, University of California, Berkeley

This early system suffered from a low signal-to-noise ratio caused by the transceiver aperture shape and the reflection of incoming signals from the adjacent strut surfaces. Following the development of the acoustic horns (described above) the researchers housed the transceiver in a small streamlined housing, or "nacelle," or stub, extending inward from the struts, which were moved outward to keep the same tetrahedron dimensions (the maximum version). The researchers found that the struts and stubs could be printed as single hollow pieces through which the ribbon cables are inserted from one of the ends. This increased the structural rigidity and permitted the struts to be reduced in cross section to the minimum possible to house the ribbon cable. Figure 7 shows the most recent design of the sensor attached to the ribbon cable.

Figure 14: Sensor Attached to Cable



Ribbon cable plugged into the ultrasonic transceiver, with omnidirectional horn (green).

Photo Credit: Ed Arens, University of California, Berkeley

The research team printed and tested several iterations of the enclosure, trying different techniques to reduce noise from signal (Figure 15). The team found that the anemometer supporting struts reflect the ultrasonic waves and negatively impact the ultrasonic signals in the receiving transceivers, resulting in a potential source of unwanted reflected ultrasonic signals. If reflected waves arrive in the receiver sufficiently soon after the original signal, they can cause noise in the received signal. To remove any possible sound reflections, the distance from a transceiver to the closest solid surface should exceed 2 centimeters (cm). The team added streamlined stubs or "nacelles" to hold transceivers away from the struts. The team developed two designs: the maximum anemometer struts are positioned beyond the maximum distance that this effect can occur (~2 cm), using arms to hold the sensors. The more compact minimum anemometer has a distance of ~1 cm. In addition, the team tried different shapes of the base to minimize reflections, discovering that the bottom base requires an arm extension to minimize the reflections.

Figure 16 (right side) shows the maximum version where the support struts are pulled outward of the transceivers with the intent of reducing the aerodynamic wake influence of the struts on the signal paths. On the left is the minimum version for a more compact application.

The vertical struts have a "teardrop" cross section facing outward to minimize and stabilize wakes within the tetrahedron. The teardrop shape is shown in the cross-section of the drawing in Figure 17.

The most recent minimum design is shown in Figure 18. Note that both types employ the omnidirectional horns.

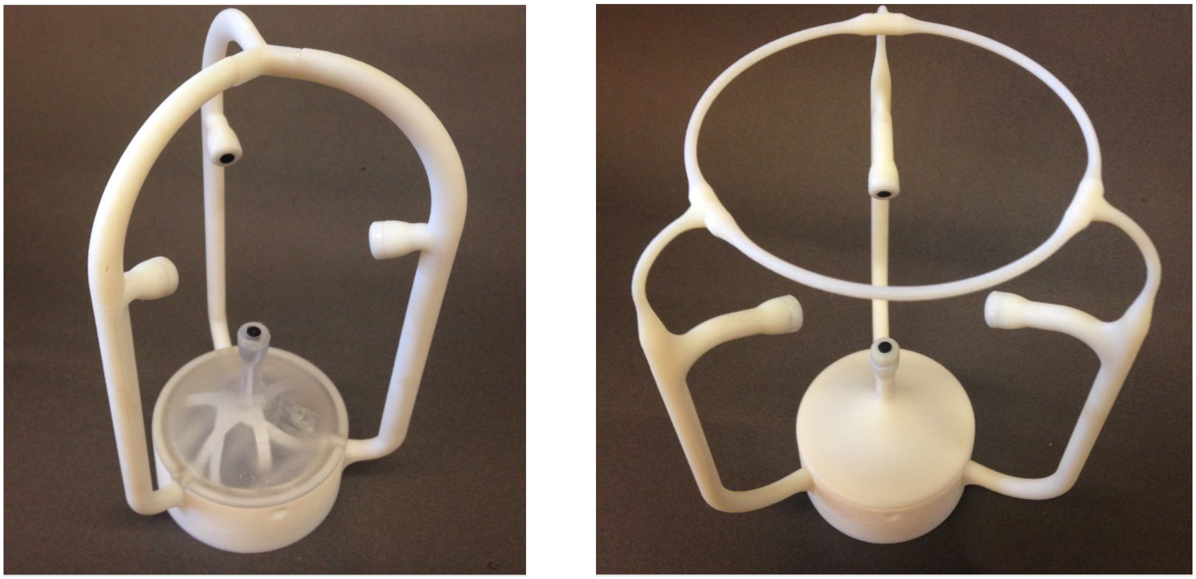
The room anemometer prototype was deliberately designed to a small dimension (6-cmtetrahedron paths) that is near its limit for detecting low air speeds. The maximum and minimum versions trade off speed measurement performance versus practicality when used as a hand-held instrument, and visual impact when in indoor monitoring applications.

Figure 15: Progression of 3-D Printed Room Anemometer Design

Left: early design with sensors in the vertical support arms. Middle: cone-shaped base, nacelles or stubs holding the sensors, arms holding the stubs. Right: Arm holding the base sensor.

Photo Credit: Vy Luu, Syung Denny Min, Ali Ghahramani, Hui Zhang, Ed Arens, University of California, Berkeley

Figure 8: Maximum and Minimum Room Anemometer Prototypes



Left: The minimum design using stubs to hold the sensors. Right: The maximum design where the armature is moved away from the center.

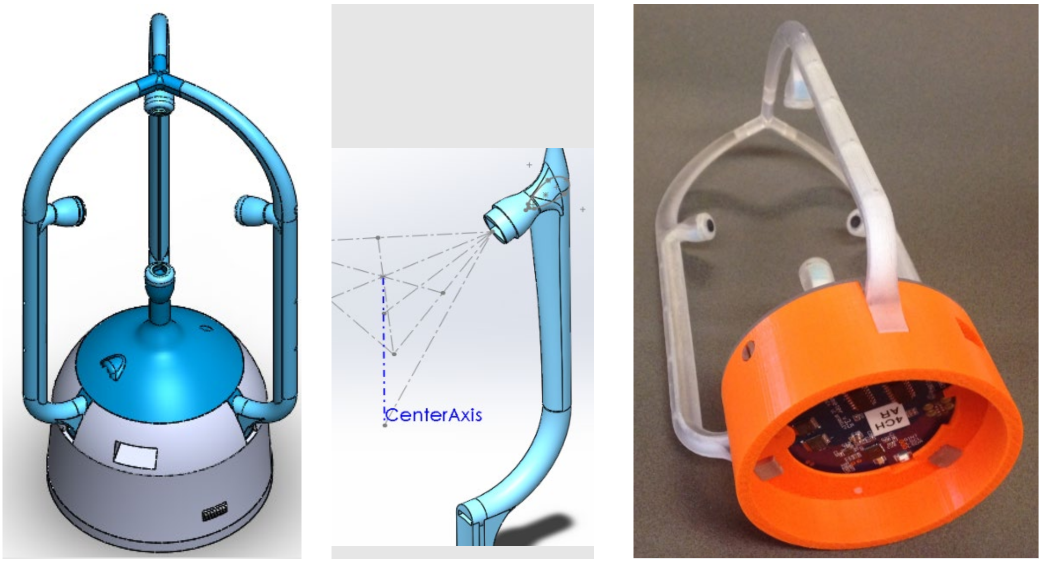
Photo Credit: Vy Luu, Syung Denny Min, and Ed Arens, University of California, Berkeley

Figure 17: Cross-Section of Room Anemometer

The cross section shows the rectangular holes for the ribbon cable and the teardrop shape of each of the three armatures that hold the transceivers.

Source: Syung Denny Min, and Ed Arens, University of California, Berkeley

Figure 18: Min Room Anemometer Prototype



Left: rendering of the Min design with space for a lithium-ion D-cell-sized battery in the base. Note the temperature sensor in top of the base on the left side. Middle: rendering of the armature. Right: View from the base of the room anemometer showing the carrier/communication board.

Source: Vy Luu, Syung Denny Min, and Ed Arens, University of California, Berkeley

Duct Anemometer

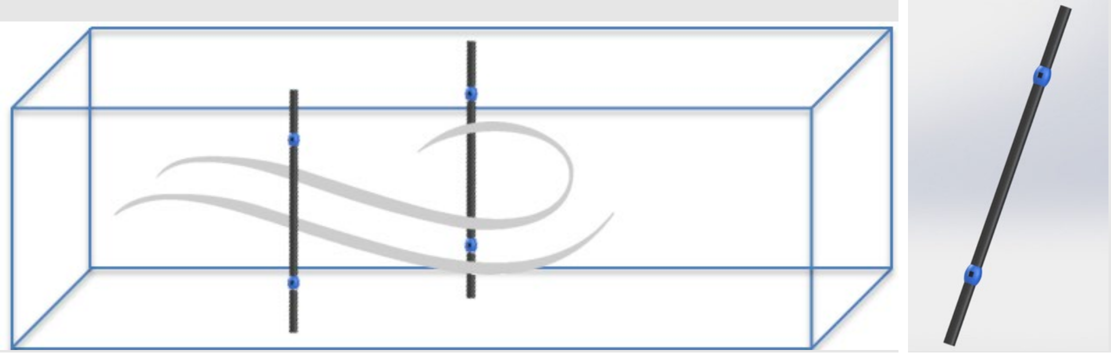
The purpose of the duct anemometer is to measure integrated air speed and volumetric flow in HVAC systems, and also key details about the distribution of air speed and temperature over the duct cross-section. The research team developed and prototyped two different designs of duct anemometer. The first configuration measures the average air flow and temperature in a two-dimensional cross-section through the duct. One version implemented a set of either two or three transceivers spaced along slender cylinders or "wands" facing each other across the inside of the duct, one relatively upwind of the other. Since the room anemometer is using four transceivers, the researchers chose to work with two transceivers per wand. A bidirectional horn at the transceiver opening amplifies signals into a vertical sheet and reduces unwanted signals, such as reflections off the duct walls. Variants of this design were tested for signal quality, such as mounting the sensors on short stubs mounted on the wands or even directly on the walls of the duct.

The second design transforms the configuration of five to seven sensors into a diamond shape called a bipyramid, which measures the three-dimensional airflow. This design provides redundancy in the air flow and temperature measurements that allow correction of turbulence and irregularity in the duct flow. This design would be built as a prefabricated flow station to be inserted into ducts or variable air volume boxes.

Cross-Section Duct Anemometer

Figure 19 shows the initial configuration of the duct anemometer: two carbon fiber wands holding two transceivers each; the wands are located near the opposite sidewalls of the duct, angled across the duct to provide a downwind distance between them.

Figure 19: Initial Concept of the Duct Anemometer



The rendering of the duct anemometer and a single wand with two transceivers.

Source: Vy Luu, Syung Denny Min, and Ed Arens, University of California, Berkeley

The researchers iterated the design of horns and wands several times over the project. The shape of horns for the duct flow anemometers is bidirectional, as described in the preceding section, to amplify signals coming diagonally across the duct from high-to-low, or low-to-high, and to reduce sounds reflected off the walls of the duct. The direct horizontal signals are the shortest and the strongest, but the horns reduce the difference in signal strength.

The cross-section duct anemometer prototype includes the transceivers with bidirectional horns mounted flush with the wand, and alternatively using a two cm-long stub to hold the sensor from the wand. The stubs are three-dimensional and other plastics. The stub design gives the horn a 20 degree tilt to aim it more equally between the diagonal and transverse sonic paths. Figure 20 shows the transceivers glued to the carbon fiber wand.

Figure 21 shows that the duct anemometer could use wands with transceiver mounted inside the duct sidewalls or the sensors mounted on the outside of the duct through the sidewalls. The length of the stub assures that the transceiver is positioned beyond the duct boundary layer, and clear of acoustic signals reflected by the sidewalls.

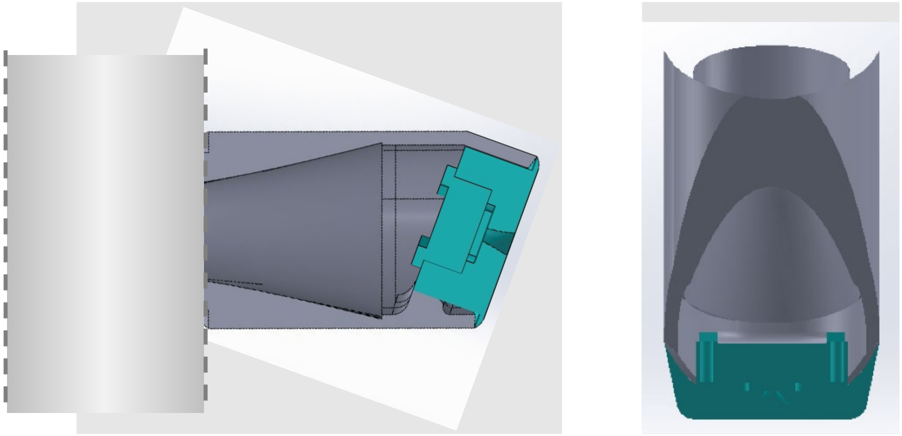
The anemometer carrier board is equipped with six ports to accommodate up to six sensors, three per side. There is also a port for the temperature sensor that must be positioned within the duct. This sensor is used in the temperature-guided velocity algorithm that underlies the system (described in the second paper in Appendix D).

Figure 9: Cross-Section Duct Transceiver in Wand

Left: Close-up of the transceiver with bidirectional horn directly attached to wand. Center: Transceiver and horn attached to wand on a short stub. Right: Wand with two transceivers.

Photo Credit: Hui Zhang, University of California, Berkeley

Figure 10: Section and Rendering of the Stub Housing Bidirectional Horn and Transceiver



Left: Rendering of the side section of the duct stub that holds the bidirectional horn. Note the angle of the sensor. Right: Top rendering of the same horn.

Source: Vy Luu, Syung Denny Min, and Ed Arens, University of California, Berkeley

Figure 22 shows the cross-section duct anemometer configuration which is designed for ease of installation for retrofits. A hole is drilled only in the bottom of the duct, allowing the wand to be slipped in upward and secured at the bottom with a custom bushing. Fixing the location of the upper end is done using the device shown below. Figure 26) shows the stiff guide wire welded to a tap screw is drilled into the upper side of the duct and extends out the bottom hole. The instrumented wand is slipped upward over this guide wire and turned to face the other wand before securing with the bottom bushing. The arrangement allows the wand to be removed and reinserted at any time without altering the wand position.

Figure 11: Cross-Section Duct Anemometer Configurations

Left: Two wands of the cross-section duct anemometer (sensors flush with wand) installed in lab testbed. Center: Close up of wand, with stubs. Right: Configuration with sensors mounted through the sides of the duct.

Photo Credit: Hui Zhang, University of California, Berkeley

Three-dimensional Bipyramid Duct Anemometer

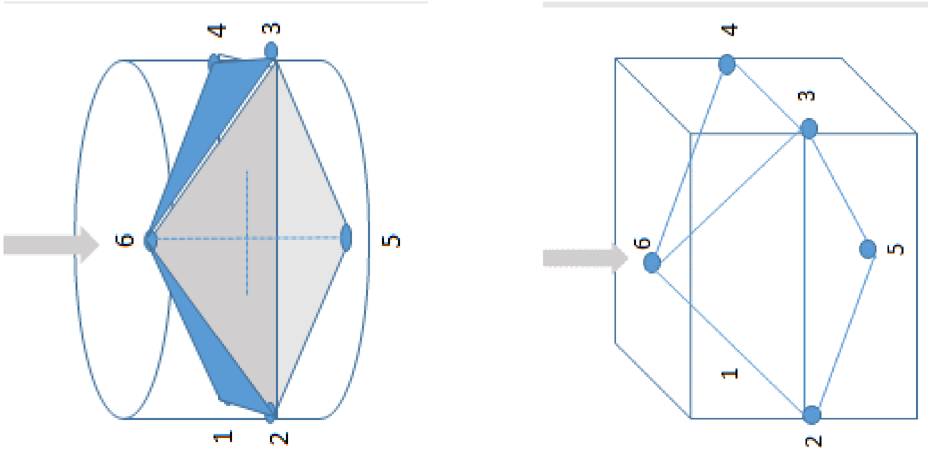
The cross-section duct anemometer with CH-101 sensors worked well in a 12-inch square test duct with flow straighteners up to six m/s wind speed. However, there were a few limitations, such as expanding the distance between the sensors. The research team realized that a different configuration or using lower frequency sensors (such as, CH-201) would work over greater distances, improve the performance in higher velocities (that is, greater than seven m/s or 1400 fpm), and improve the resilience due to sudden temperature fluctuations (such as that caused by the upstream reheat fan coil) or turbulence (such as that caused by duct structure [for example, elbows], or damper position changes). The lower frequency CH-201 sensors are not currently available, so the team pursued a new configuration, leveraging the success of the room anemometer configuration. Figure 23 shows the simple tools required for installation and the new configuration. With a pair of sensors in the center of the duct, the six transceivers create a diamond shape (visualize pasting two Giza pyramids (single apex, square [four-sided] base, held together at the base), more precisely known as a square bipyramid or four-gon right bipyramid (Figure 24).

Figure 12: Installation of the Cross-Section Duct Anemometer in Existing Ducts

Left: Hollow shafted socket wrench for inserting tap screw in top of duct; Right: bushings and caps for supporting and orienting the wand at the bottom.

Photo Credit: Ed Arens, University of California, Berkeley

Figure 13: Three-Dimensional Bipyramid Duct Anemometer



Configuration of six ultrasonic sensors in a diamond shape, known as a right bipyramid, shown inside a circular duct (left) and square duct (right).

Source: Ed Arens, University of California, Berkeley

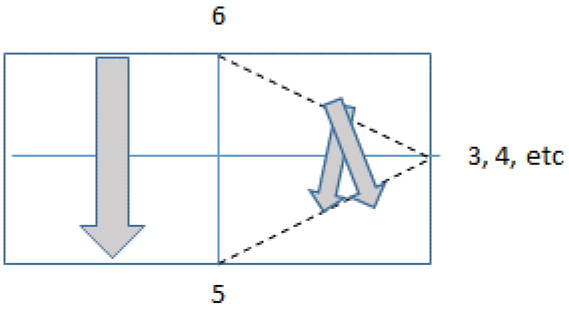
The bipyramid configuration uses the CH-101 transceivers with the omnidirectional horns. The distance ranges are cut roughly in half, and the design compensates for turbulence in the duct. The axial dimension is parallel to the nominal flow direction; the four-polygon base is perpendicular to flow. The transceivers at the apexes receive the signals from the four transceivers around the base. The paths going to (5) from a given base transceiver (such as 1) will be directly downwind of the path going from (1) to (6). They will measure the same wind and by averaging them they will compensate for any errors. The axial dimension can be compressed to provide the optimum cross-flow angle for both the upwind and downwind paths.

There are several advantages to the bipyramid design, based on the n-polygon base:

- The lengths of the longest sonic paths are now less than half of the cross-section duct anemometer.
- The upwind/downwind symmetry of the paths means that airflows producing bias in the upper path (such as turbulence resulting in airflows close to perpendicular to the nominal air flow) will be compensated for directly in the path below it.
- This configuration should detect temperature and airspeed variation across any axis (vertical, horizontal, or diagonal), unlike the cross-section duct anemometer.
- The center apex produces a much simpler solution for circular ducts.
- One of the stalks that holds the center sensor can also host the temperature sensor in the center of the duct.

Figure 25 shows the cross-section of the duct and the direction of airflow.

Figure 14: Redundant Measurements Compensate for Errors Due to Turbulence

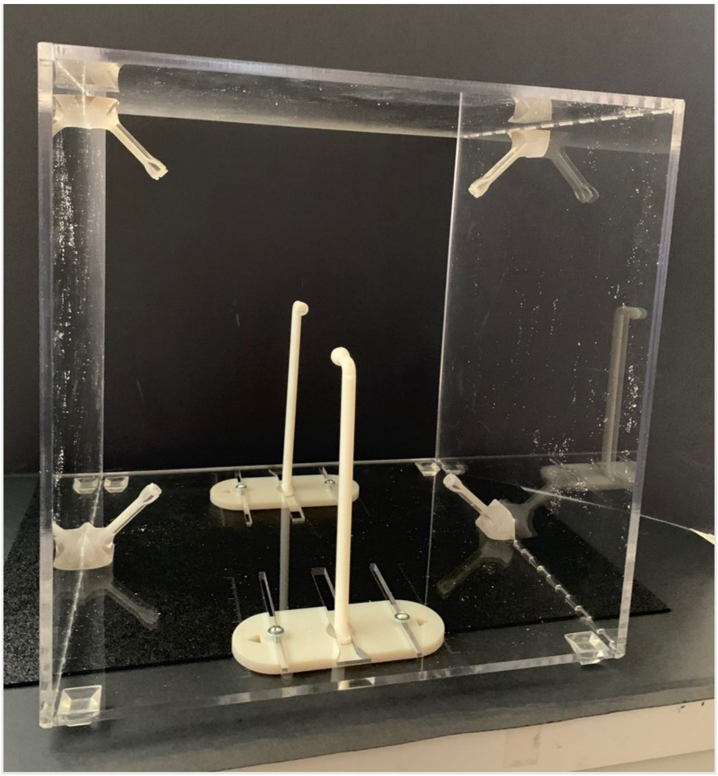


A cross section of duct with flow moving top to bottom. Averaging delta time-of-flight for paths 6-3 and 5-3 corrects cosine errors caused by lateral turbulence and direction changes. (A pure axial flow [left] would produce identical readings on both paths.)

Source: Ed Arens, University of California, Berkeley

Figure 26 shows the demonstration of the duct testbed with multiple sensor locations.

Figure 15 Configuration of the Bipyramid Duct Anemometer



A testbed showing all six sensor locations, with two axial sensors rising on struts to the center of a square duct, and four sensors entering at the corners.

Photo Credit: Hui Zhang, Ed Arens, University of California, Berkeley

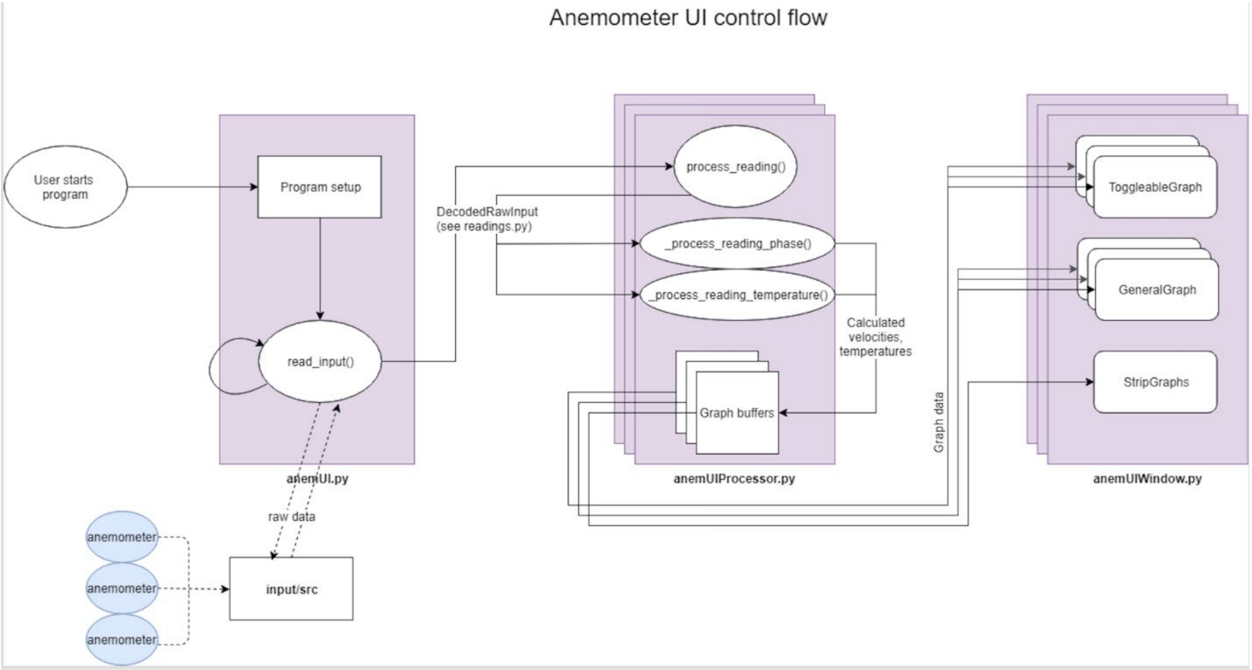
CHAPTER 3:
Data Output and User Interface

This chapter describes the ultimate output: the translation of the raw data from the ultrasonic signal into an air flow measurement. One of the first steps was to create a user interface to visualize the data. The next section describes the final user interface design.

User Interface

Figure 27 shows the process flow diagram used to design the user interface. At the left of the figure, the process starts with the program setup and reading the input from the raw data. The middle section shows the processing of the data, both air flow, velocity, and temperature. The right section shows the various graphs that display the data.

Figure 27: Schematic Diagram of the Data Visualization in the User Interface



The schematic shows the data flows from left to right, and names the different Python packages used to decode, process, and graph the data.

Source: Megan Zhu, University of California, Berkeley

Room Anemometer

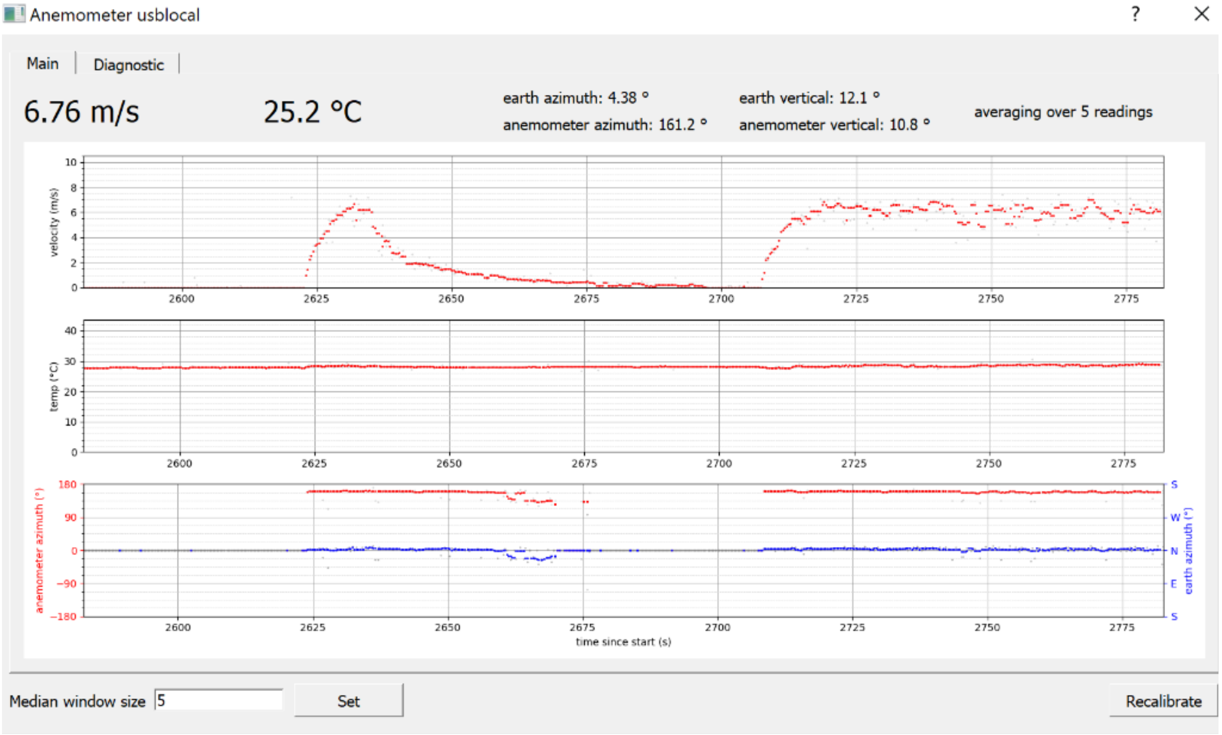
The room anemometer user interface consists of a main screen and two diagnostic screens. In Figure 28, the Main Screen shows the real time values of:

(Top) air speed (averaged over five readings as seen in dialog box ‘median window size’),

(Middle) sonic temperature (calculated, not measured)

(Bottom) air flow horizontal azimuth angle (according to the earth’s global coordinate system [blue] and in the local coordinate system relative to the anemometer (red) and air flow vertical approach angle (both global [earth]) and relative to the anemometer (local).

Figure 28: Main Screen of the Graphical User Interface for the Room Anemometer



Anemometer usblocal

6.76 m/s

25.2 °C

earth azimuth: 4.38 °

anemometer azimuth: 161.2 °

earth vertical: 12.1 °

anemometer vertical: 10.8 °

averaging over 5 readings

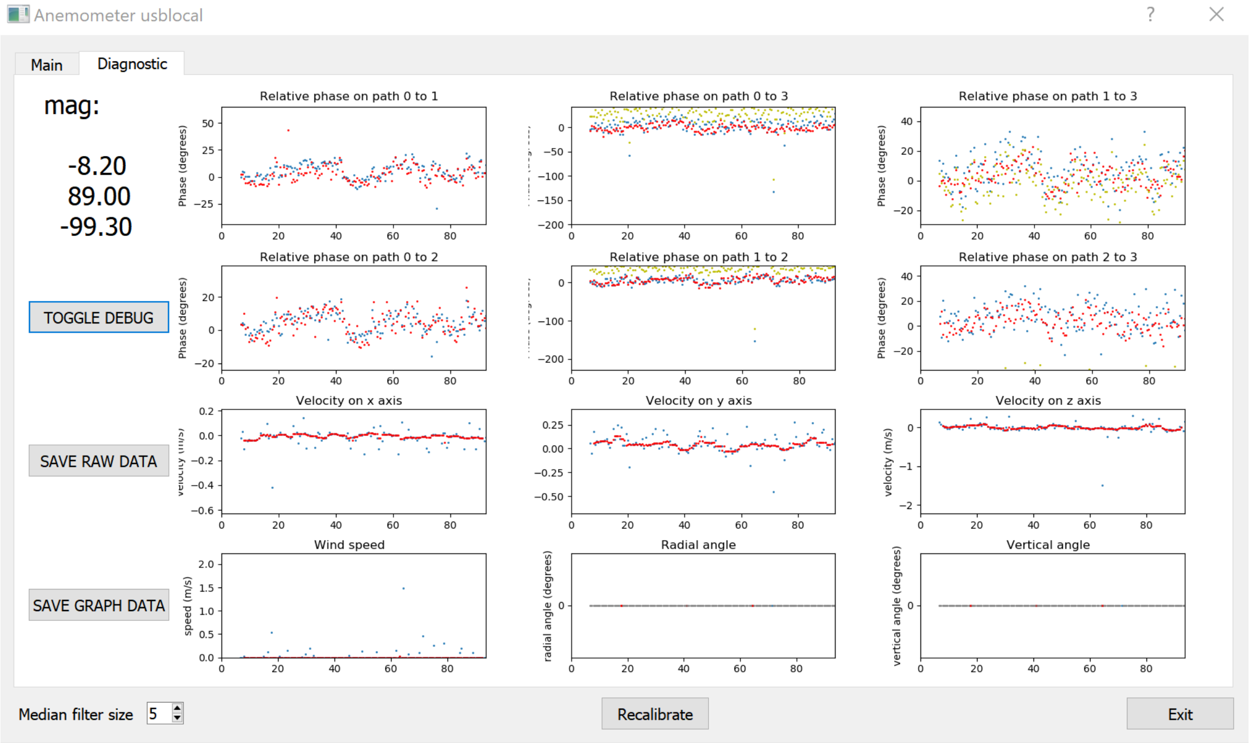
Median window size 5

Main screen shows relative air speeds in both directions for all six paths; note that 0 azimuth angle is air from the north. A fan, initially off, is turned on, then off, then on again. No direction is displayed at air speeds near zero.

Source: Ali Ghahramani, University of California, Berkeley

The diagnostic screen (Figure 29) provides more detailed information, such as the raw data for each sonic path, the three hard iron magnetometer readings, and the tilt angles.

Figure 29: Example Graph From User Interface for the Room Anemometer



mag:

-8.20
89.00
-99.30

Median filter size 5

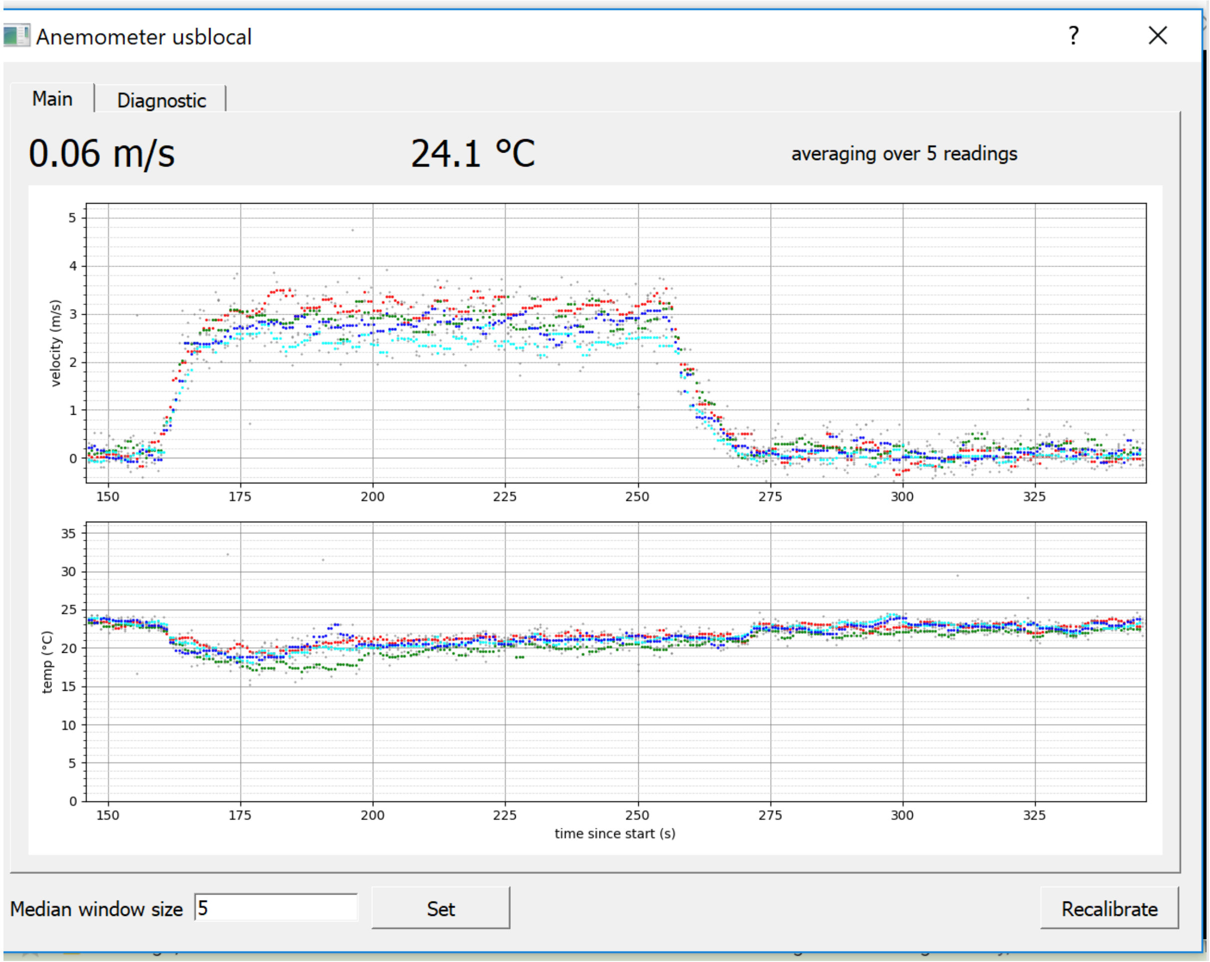
The diagnostic screen shows more detailed data.

Source: Ali Ghahramani, University of California, Berkeley

Duct Anemometer

The duct anemometer user interface consists of a main screen and a diagnostic screen. In Figure 30, the top graph shows the real time values of air speed (averaged over five readings as seen in dialog box ‘median window size’). The bottom graph shows the real time values of sonic temperature, calculated for each path.

Figure 16: Main Screen of the Graphical User Interface for the Duct Anemometer



0.06 m/s

24.1 °C

averaging over 5 readings

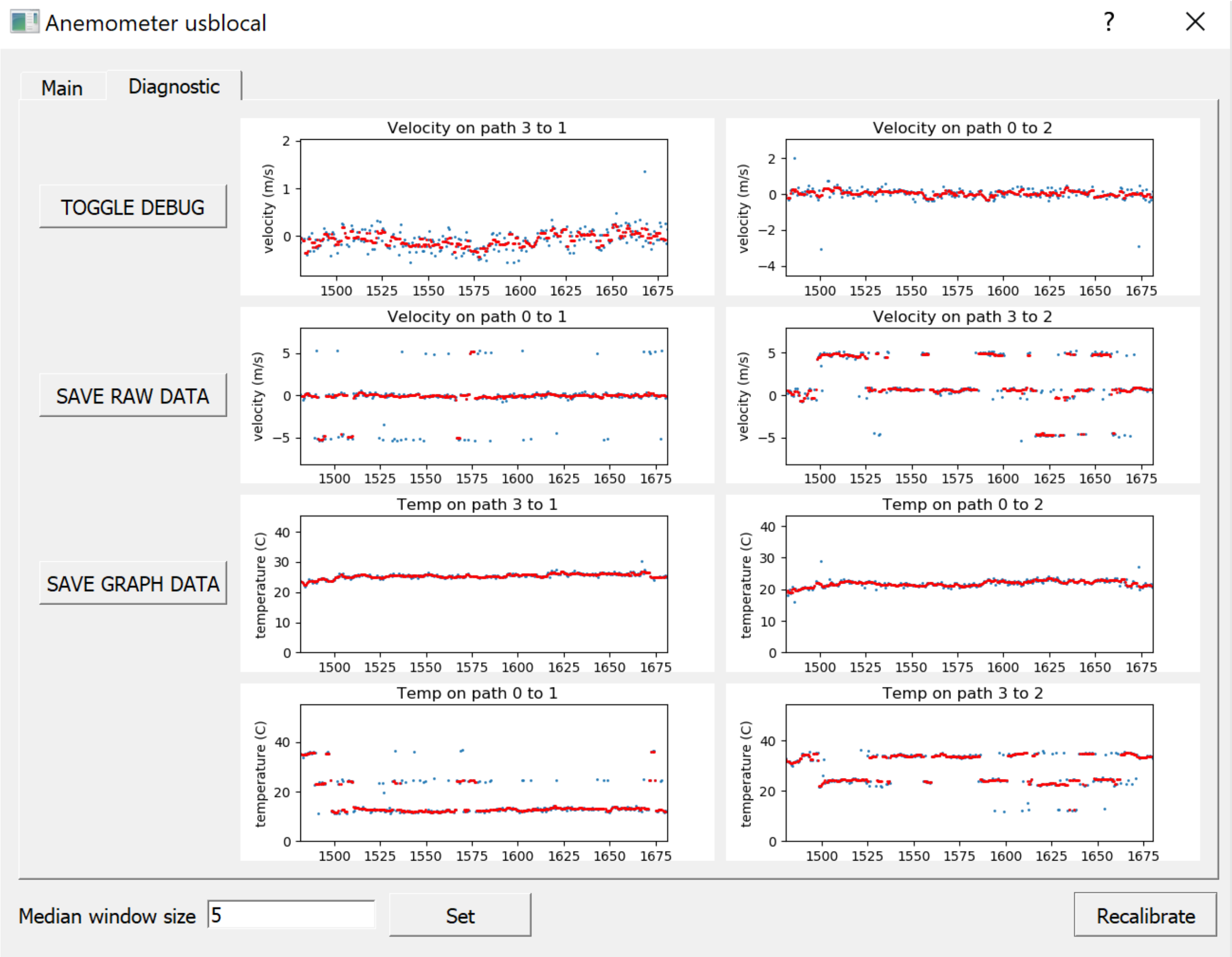
Median window size 5

Main screen of the four-sensor duct anemometer. **gnostic**

Source: Ali Ghahramani, University of California, Berkeley

The diagnostic screen (Figure 31) provides more detailed information, such as the raw data for each sonic path, and the calculated sonic temperature. The diagnostic screen (Figure 32) provides the data screen showing recalibration after a phase breakdown in which a transducer had skipped a cycle.

Figure 17: Diagnostic Screen of the Graphical User Interface for the Duct Anemometer

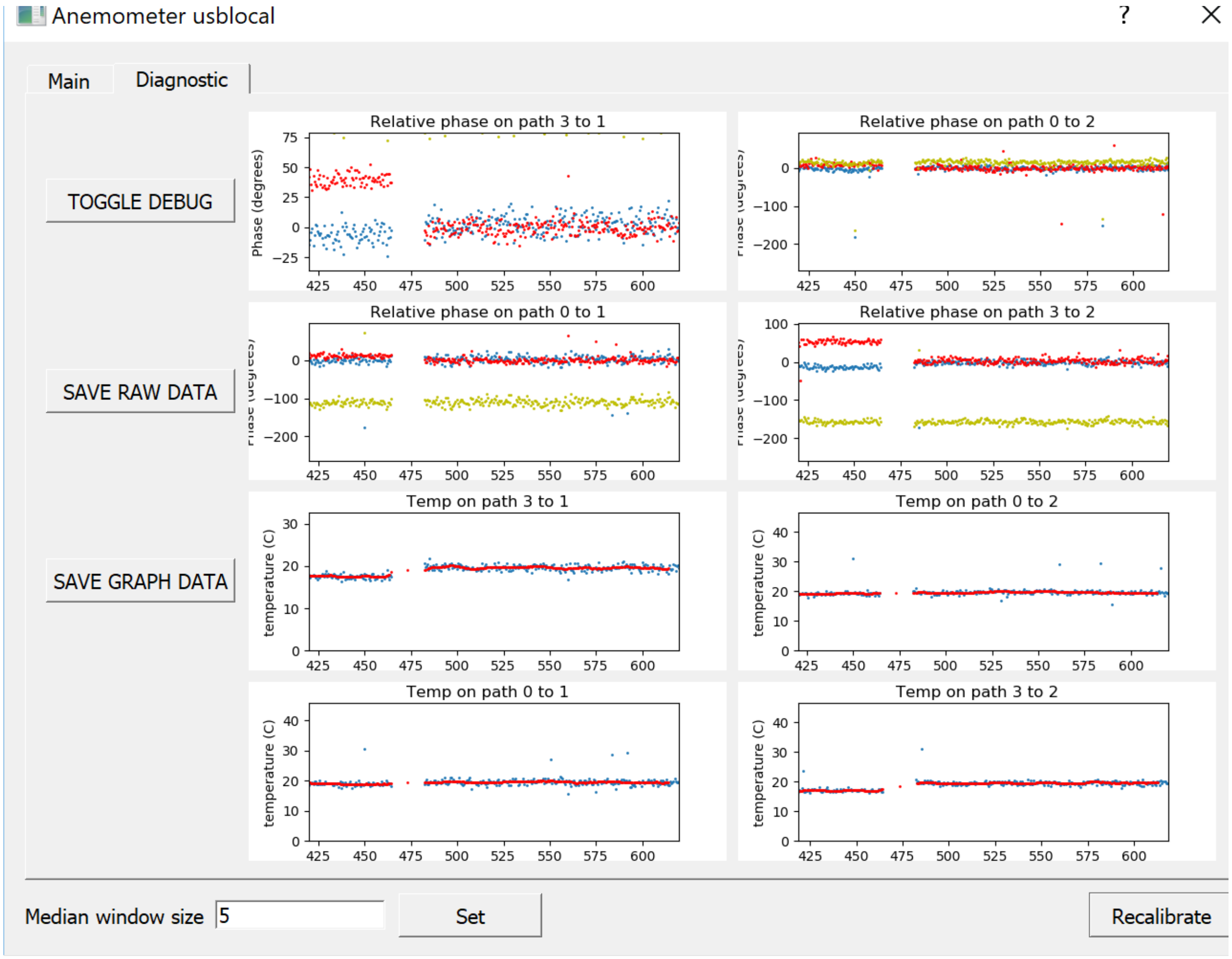


Median window size 5

The diagnostic screen of the four-sensor duct anemometer shows the air speed and temperature for each path (sensors numbered 0, 1, 2, 3).

Source: Ali Ghahramani, University of California, Berkeley

Figure 18: Example Diagnostic Screen for the Duct Anemometer



Median window size 5

Still-air test showing recalibration (gap) after a phase breakdown in paths 3 to 1 and 3 to 2, in which the #3 transducer had skipped a cycle.

Source: Ali Ghahramani, University of California, Berkeley

The code for the user interface is found at https://github.com/AliGhahramani/Anemometer

CHAPTER 4:
Promising Applications

This chapter describes potential applications for the anemometers, in a roughly prioritized list. The list was derived from a series of team brainstorming sessions. They focus on the HVAC market and represent some of the most promising applications for the ultrasonic anemometers.

Outdoor Air Flow Measurement

Description

Building HVAC systems are required to provide a minimum amount of outside air into the building. To control the amount of outside air entering the building, building HVAC systems measure the outside air flow (either directly or indirectly). "Airflow measurement stations" is the term usually applied to duct and outside air intake flow measurement products.

A typical approach to outside air measurement is to have two separate dampers on the outside air intake, one with an airflow measurement station or differential pressure measurement used to measure outside air flow for ventilation, and the other used for an economizer. The reason that one airflow measurement station on the entire outside air intake is not common is because few airflow measurement stations products are accurate enough at the low velocities that occur at minimum ventilation (~10 to 15 percent of maximum flow, or even lower). The second damper section for the economizer typically does not have an airflow measurement station so the total flow through it is unknown. If only the airflow through the minimum outside air section is measured (which is typical to reduce costs), more complex control logic is required to enable and disable minimum outdoor airflow control, as shown in American Society of Heating, Air-Conditioning, and Refrigerating Engineers, Guideline 36. If airflow through both the minimum outside air section flow and economizer sections are measured, then control logic is far simpler. The ultrasonic anemometer has the potential to accurately measure the full flow of outside air, improving outside air control in buildings and decreasing associated measurement costs.

Discussion

One potential issue with the ultrasonic duct anemometer is the depth of duct required to provide the upstream and downstream distance required by the ultrasonic duct anemometer. This may be a limiting factor because there often is no downstream depth available for the outdoor airflow measurement. Several currently available anemometers (such as those by Ebtron, Air Monitor, Ruskin, and Paragon) only require a one-foot duct length when flow straighteners are used.

The ultrasonic duct anemometer developed through this grant could be assembled into a duct length as short as one foot by using multiple extra sensor wands, with short zig zags, across the face of the outdoor air intake. The CH-201 sensor with its one-meter (m) range would be more appropriate for this task than the CH-101 with its 0.25 m range. It is likely that a honeycomb flow straightener would be necessary at the face of an outside air damper.

Average Air Temperature Measurement in Air Handlers

Description

Another promising application of the ultrasonic anemometer is measuring average air temperature and measuring temperature asymmetry in air handlers and ducts downstream of economizer mixing plenums and heating or cooling coils. Due to cost considerations, most conventional sensors used for this purpose are single point measurements. Premium systems specify averaging-sensors because single-point sensors are highly inaccurate due to imperfect mixing in economizers and asymmetric heat transfer through heating or cooling coils. The averaging sensor string can be 25 feet long, which can be very costly for the sensor and its installation. The ultrasonic anemometer sensor might be less expensive and more accurate than averaging temperature sensors.

Poor air mixing can lead to temperature asymmetry, which can cause freezing local sections of coils. Measuring this temperature asymmetry could lead to control sequences to prevent coil freezing.

Mixed air temperature measurements are a good way to comply with Title 24, Fault Detection and Diagnostics requirements. Averaging sensors are much better and could be required if there was a lower cost solution.

Discussion

Similar to outdoor air flow measurement, averaging temperature applications often occur in duct sections with large turbulence within a short distance of duct changes and/or equipment. The ultrasonic anemometer must be accurate in these scenarios to have good market penetration for HVAC applications, as well as be competitive in cost to traditional averaging sensors combined with airflow monitoring stations.

Variable Air Volume (VAV) Box and Terminal Unit Airflow and Temperature Measurement

Description

VAV boxes are used to control airflow and the temperature of the airflow to different zones throughout the building. To maintain pressure independence from all other VAV boxes in the system, the VAV box must be able to control to an airflow setpoint, which requires measuring the airflow through the VAV box. To accurately measure airflow, VAV box inlet sizes are smaller than standard ductwork, thus causing relatively high pressure drops through the assembly. Additionally, to control to a discharge air temperature setpoint, the VAV box with heating coils must measure its discharge air temperature. Current VAV boxes measure airflow using pitot-type amplifying flow crosses in the inlet of the VAV box and measure discharge air temperature using a single-point temperature sensor far enough downstream of the heating coil to minimize the risk of measuring stratified air.

The ultrasonic anemometer would allow for positioning airflow/temperature sensing directly downstream of a VAV box or another terminal unit type. This revolutionary approach would replace the discharge air temperature sensor inserted into the plenum downstream of VAV box and the flow-cross upstream of the VAV damper.

With temperature measurement directly downstream of the coil, it becomes possible to measure average temperature off the reheat coil, avoiding issues of stratification, as well as determining if the coil valve is passing/leaking.

With the ability to measure airflow velocity down to 20 fpm (0.1 m/s; very slow), the VAV box inlet area becomes irrelevant and one could make all the VAV box duct inlets the same size, and all boxes can be full-size (largest VAV box size available that fits in ceiling space). This approach saves energy by reducing pressure drop at the box inlet and reheat coil and also reduces first cost by simplifying construction (same boxes everywhere). There is also no longer a requirement for field calibration of the VAV box flow sensor which results in additional labor savings.

Discussion

There will always be a few feet of straight duct length off the plenum because there is always duct downstream of VAV discharge and reheat coils; therefore, any issue of the ultrasonic anemometer requiring a length of straight duct is irrelevant for this application. This application is most likely where the ultrasonic anemometer will be most disruptive.

The flow field downstream of the damper in the VAV box is highly non-uniform, especially when that damper is mostly closed. Fortunately, this does not pose an issue for a VAV box with a reheat coil as the coil is an effective flow straightener, and the anemometer is downstream of the coil. However, for cooling-only VAV boxes, the anemometer may need to be upstream of the damper to take accurate measurements.

The American Society of Heating, Air-Conditioning, and Refrigerating Engineers, Guideline 36 standard VAV box sequences would still apply in this new application, with a few potential additions:

There would be no need for the time averaged ventilation option because there would effectively be no controllable minimum airflow given the low range of the ultrasonic anemometer

New alarm to indicate a reversal in airflow direction (stack effect or exhaust) when the damper is closed

Improved leaky damper alarm—set threshold to two percent of cooling maximum rather than current 10 percent

New alarm to indicate severe air temperature stratification off the reheat coil

Flow Sensing at VAV Diffusers

Description

VAV diffusers provide airflow control at the diffuser itself. Some VAV diffusers have electrically-powered dampers, while the traditional approach is to be thermal-wax driven. Neither approach measures flow. A potential application of the ultrasonic anemometer would be to eliminate the VAV box and just use VAV diffusers. However, there is still a requirement for a heating coil somewhere which may be similar in price to a full VAV box. A new VAV diffuser with airflow measurement would mean zero diffuser balancing and zero VAV calibration.

Discussion

The variable air volume diffuser approach may be expensive and potentially noisier than traditional VAV box approach, but can provide improved comfort by allowing every room to be its own thermal zone. The ultrasonic anemometer could increase the market of variable air volume diffuser. However, the length of duct required for the ultrasonic anemometer will likely preclude this application.

Testing and Balancing

Description

Typical HVAC specifications require that the test and balance contractor test airflow at all important parts of the system, including the air handler, VAV boxes, and diffusers; and often at multiple airflow setpoints. Using the ultrasonic anemometers has the potential to reduce the cost of some of this testing and balancing work.

Flow capture hoods are used extensively in testing and balancing. Flow measurement down to 25cfm is required. A higher accuracy flow sensor could improve hand-held flow hoods. Similarly, flow cross arrays are used to measure airflow at air handlers and some of these measurements may not be required (or made easier) through the use of the ultrasonic anemometer.

Discussion

Another potential testing and balancing application (though less promising) would be to replace difficult-to-access manual balancing dampers with electronic balancing dampers with flow measurement. Balancing dampers (such as for diffusers or branches) above a hard (non-suspended acoustical) ceiling are difficult to access. They are also difficult to actuate and require expensive solutions such as remote actuators using cables and hidden access ports, or a small motor to set the damper with a hidden wire to plug-in a hand-held controller that remotely powers the motor. An inexpensive acoustic anemometer could be used to make a system self-balancing, where flow feedback controls the small damper actuator. A product that was used once for initial balancing and then left in place is worth $50 to $100 compared to current options. Using an ultrasonic sensor for balancing eliminates the requirement to use a portable flow hood. The solution directly balances the damper position and can also be used for test and balance temperature measurements. The cost effectiveness of this solution would be dependent on labor savings from testing and balancing work compared to the added cost of the components.

Corrosive Environment Applications

If the ultrasonic anemometer sensor/receiver chips were protected by a weatherproof coating/cover, it could open up other options for sensing in contaminated or corrosive environments.

Commercial Kitchen Ranges

Demand controlled ventilation is now in the building energy codes (American Society of Heating, Air-Conditioning, and Refrigerating Engineers, Standard 90.1; California Title 24) for certain conditions that require variable speed exhaust, correlated to temperature of surface or level of smoke to determine ventilation needed. Range hood smoke capture is the critical performance requirement and room and "near hood" airflow measurement may be able to measure capture effectiveness. If capture effectiveness is measured, controls could reset to use only the required airflow for smoke capture, saving a huge amount on makeup air conditioning and also fan energy.

Fume Hoods

Air flow of 100 FPM across the face of hood is the minimum (0.5 m/s). The velocity is allowed to be reduced to use 60 fpm when no one is present in front of the hood. Improved face velocity measurement, including determining if flow is laminar and that no flow reversal is occurring, could potentially be used to reduce face velocity even further. Fume hood makeup air is often 100 percent outside air that needs to be conditioned, costing up to $5 per CFM per year, so substantial savings are possible with small reductions in face velocity or airflow.

However, it is not yet clear where an acoustic duct anemometer could be mounted on a fume hood because of the need for a cross-duct angle of at least 20 degrees between the transmitter and receiver. Fume hood redesign might be required. There is potential for a sensor located on the sill and roof of the fume hood opening.

Hospital and Laboratory Room Pressurization Control

Examination rooms use several VAV zones with common return (not operating rooms). Typical practice is to average all the flow inputs to come up with setpoint for return dampers, rather than measure return flow directly. Return flow is not measured because of sensing issues: Cotton/wipes can get sucked into pitot tubes or hotwire sensors—but this would not be a problem for this new acoustic anemometer. In general, pitot tube sensors get clogged. Vortex shedding solutions are supposed to unclog, but are expensive. Accuvalve[7] measures eddy shedding on the element's backside, so it can also function in contaminated airstreams.

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[7] A product of Accutrol LLC.

CHAPTER 5:
Production Readiness Plan

Because this project team will not be engaged in the manufacture of the final anemometers (excepting at most the micro-electromechanical systems sensor elements), this chapter describes only the parts of final manufacturing that the team has direct experience with—the requirements and costs of micro-electromechanical systems production, the cost of the populated carrier board, and IP information.

Cost

The total estimated cost of the anemometer at volume is $65, $102, and $118, with the lowest number reflecting little to no enclosure cost (such as sensors mounted directly to duct walls) and the other numbers reflecting the number of sensors and cables for the room anemometer (four), compared to the duct anemometer (six). The manufactured cost of the integrated carrier and communication board described in Chapter 1 is around $30, based on a 10,000-board order. The cost of the CH-101 transceiver varies by volume (contact Chirp Microsystems sales [info@chirpmicro.com] for availability and pricing), but can be estimated at about $5 each. An estimated cost for the enclosure (assuming injection molded) is $10. The cabling is around $3 per cable (four to six cables per anemometer), or one could use a flexible printed circuit board. The assembly cost would run around $30 per unit in the Bay Area.

Intellectual Property Information

An invention disclosure and provisional patent (Arens et al, 2019) has been filed with the University of California, Berkeley concerning:

The tetrahedral organization of the room anemometer and its signal processing.

The cross-duct organization of the duct anemometer, and its signal processing.

Various bipyramidal organizations of the duct anemometer and its signal processing.

The temperature-guided and magnitude-guided signal processing for time-of-flight measurement.

Path Towards Commercialization

The researchers met and visited with several potential manufacturers:

Davis Instruments in Hayward California (https://www.davisinstruments.com) in October and December 2017. The research team demonstrated the room anemometer to Davis Instruments. Davis instruments has been making environmental measurement systems for over 50 years, and were interested in potentially developing the room anemometer for outdoor use.

Swegon in Sweden, https://www.swegon.com/ from November 2018 to March 2019. Swegon signed a Non-Disclosure Agreement, then the researchers presented slides and video to them in a web conference in February 2019; Swegon received a room anemometer in late March 2019 and will test it. Swegon is interested in the potential of the room anemometer to replace the $1,500 air flow sensors in their test facility as well as integrating the duct anemometer in their small round ducts used for balancing air flow between rooms.

Bayside HVAC, local representative for Air Monitor (https://www.airmonitor.com/) in Santa Rosa, California, and TSI instruments from February to March 2019. The researchers presented both the room anemometer and duct anemometer to members of Bayside HVAC, who then pitched the idea to Air Monitor and plan to demonstrate the room anemometer in a meeting on April 2019 to TSI. Both Air Monitor and TSI are manufacturers of hot-wire or thermal air flow instruments for both handheld tools for spot measurements, and for integration into ducts for commissioning and troubleshooting as well as for stationary monitoring in ducts and outside air stations.

TSI (https://www.tsi.com/). Manufacturer of a wide range of measurement and instrumentation equipment for a wide range of applications and an industry leader in air flow measurement. They have expressed interest in the advantages ultrasonic technology offers over current technology and would like to lead the market in adopting it.

Price Industries (https://www.priceindustries.com/). Project partner received a room anemometer and used it to monitor duct airflow; they are interested in the duct anemometer and will receive a bipyramid anemometer when it is ready. The project team interviewed representatives from the product development groups for typical variable air volume terminal units and critical facility control valves. The manufacturer is currently reviewing the costs which are key to understanding whether replacing flow cross makes sense.

The team has shared product specifications and presentation with several other manufacturers, including Krueger, Ruskin, and Ebtron. All indicated interest in the technology and the desire to learn about it.

TRC also interviewed several manufacturers of HVAC equipment and measurement tools to understand barriers; a summary follows.

Existing Technologies

Air Monitor and Ebtron are two leading air flow measurement device manufacturers for HVAC outdoor air flow and duct/fan mounted air flow measurement. The products obtain air flow measurement using either hotwire thermal sensors or differential pressure sensors.

Manufacturer catalogs claim the measurement accuracy could be up to 2 percent. The accuracy depends highly on the number of sensors used because airflow in ducts is never uniform. The catalogs also claim airflow range from 0 to 3000 fpm (~15 m/s); one manufacturer stated that an upper limit of 4000 fpm (20 m/s) is getting close to what is required. This is much higher than the current duct anemometer can measure, which is 6 m/s. However, 75 fpm (0.4 m/s) is a realistic usable long-term lower limit according to an email communication with one of the manufacturers, and it requires calibration over time. The fact that the low limit of the duct anemometer is 0.2 m/s (40 fpm) is "outstanding" according to one manufacturer. In addition, the duct anemometer does not require calibration.

Cost and Price

Because air velocity is never uniform in HVAC applications, flow probes or flow cross sensors are used to provide multiple measurements across the duct section to improve accuracy. For flow probes that use thermal dispersion sensors, each sensor is an added cost. As a flow meter's accuracy improves with more probes and sensors, the price is also substantially more expensive. The price of a duct mounted air flow meter for small ducts (24-inch by 24-inch) ranges from $1,000 with one probe containing three sensors to more than $2000 with three probes, each with three sensors. The price of a flow meter for large ducts (106-inch by 120inch) ranges from $3000 with four probes (each with four sensors) to $4,500 with four probes (each with eight sensors); adding one sensor amounts to an additional $100 to $200 increase in price. Thermal dispersion flow probes are normally duct-mounted or fan-mounted to measure air flowrate of a HVAC system.

Note that these are prices to the owner, which could be 10 times higher than the cost of goods, according to a representative of one of the manufacturers. Each transaction between manufacturers and the owners (such as distributor and contractors) typically carries overhead, as each has its own markup. He also reveals that on the low end, the cost of goods including labor and parts is less than $100, but this number is for probes with one or two sensor nodes.

Compared to the flow probes with thermal dispersion sensors, a flow cross used in VAV boxes is much cheaper. As a flow cross measures air velocity based on differential pressure, there is no substantial additional cost with multiple measurement points. As one manufacture representative revealed, the material cost of a flow cross, and the pressure transducer, is about $10.

Manufacturer's Perspective

One engineer and one sales representative feel that the duct anemometer is potentially a game changer in air flow measurement for many applications, such as hospital patient exhaust ducts that are contaminated with lint, that renders sensors in the duct useless in a few months, lab air flow where corrosive agents are in the airstream, and depending on the cost and straight runs required, could replace other air flow sensing technologies. One rep suggested that the micro-electromechanical systems-based sonic anemometer could be as disruptive as the thermal anemometer was 30 years ago.

Although most sales representatives and manufacturers interviewed have indicated interest in the technology, none have a concrete plan to consider the opportunity to further develop the prototype. Ultrasonic anemometers have been around for a few decades, and are still viewed as expensive.

Manufacturers agreed that the prototypes need more testing. One manufacturer suggested more rigorous performance testing of the duct anemometer and comparison to existing technology is important to decide if they would like to further develop the product. Cost of the prototype and costs associated with redesigning existing HVAC equipment are also key to understanding if there is market for the technology.

In general, the duct anemometer would need to measure airflows up to 3000 fpm (15 m/s) and possibly 4000 fpm (20 m/s), with accuracy of ±3 percent over an acceptable range (400 to 5000 fpm (2–25 m/s)) to be competitive. Future studies need to include different upstream/downstream conditions, higher velocity range, and larger duct sizes. The measured temperature accuracy at 32.4°F (0.2°C) is excellent, but one manufacturer wanted to know how it varies with a stratified profile.

Several manufacturers mentioned the most attractive benefit is working in particulate or dust-laden air.

In addition, one vendor suggested that the “not invented here” syndrome may also play a role. The not invented here syndrome is a corporate cultural phenomenon where a company avoids using products of external origins. Response from one of the manufacturers implied that they have investigated a similar technology previously, but decided not to pursue further due to little benefit in cost and performance.

The researchers will continue to pursue the bipyramid duct anemometer as well as the lower frequency CH-201, both may allow higher air flow measurement up to 4000 fpm (20 m/s), improve accuracy, and use in larger ducts.

CHAPTER 6: Discussion

This chapter provides a discussion of the anemometer prototype design progression, potential energy savings, and next steps.

Design Progression

The progress of this project took several twists and turns over the 3.5 years. The first design pivot occurred early in the project, with a major paradigm shift in ultrasonic design—the room anemometer design shifted from three dedicated pairs of ultrasonic transceivers to four transceivers in a one-pitch, three-catch configuration (three transceivers listening to each send).

The initial signal processing was found to have unacceptable noise, which was a serious obstacle and led to nearly a year of trial and error in testing various algorithms and filters. The research team developed a pair of approaches using a different part of the application-specific integrated circuit output (phase instead of magnitude), and improved the signal using temperature compensation and heuristics.

Chirp Microsystems iteratively improved CH-101 over the course of this project; at one point, the application-specific integrated circuit was resetting when the transceiver was exposed to ambient light. Chirp resolved this issue. Chirp Microsystems also developed a solution to dust issues by adding a cover. Chirp developed horns—omnidirectional for room anemometer, and bidirectional for cross-flow duct flow applications; however, the researchers recently discovered problems with the bidirectional horns.

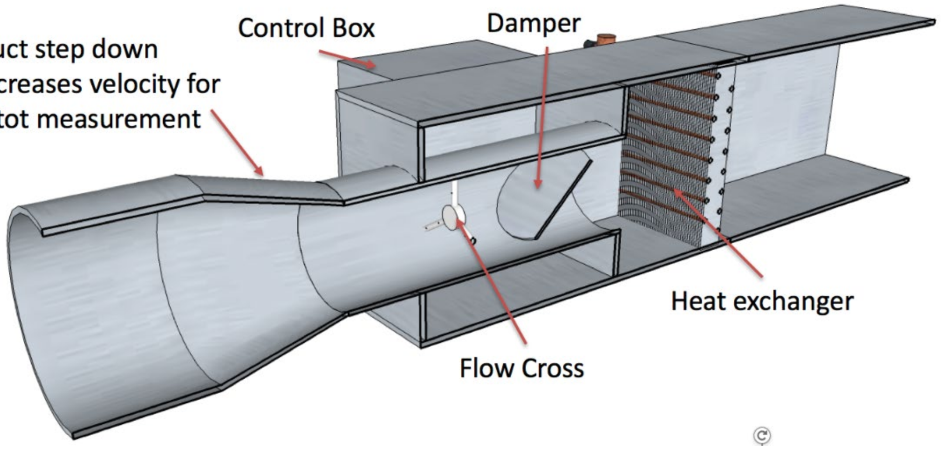
The carrier and communications board underwent several iterations as well. The initial board used 3 volts, which required stepping up from the native 1.8 volts application-specific integrated circuit operation. The carrier board was converted to 1.8 volts for high-efficiency operation from a D-size lithium battery, and eliminated the voltage stepping. The project eventually included a wired output in addition to the wireless communication. An integrated temperature sensor was added for all anemometers.

The initial cross-section duct anemometer configuration was limited to 12-inch duct application due to greater noise to signal ratio beyond this dimension. Fairly late in the project, a new configuration was developed using a bipyramidal configurations that could use five to seven transceivers built into preassembled flow stations.

Potential Application and Savings

The research team evaluated several potential applications, outlined in Chapter 4. The consensus of the team suggests that most promising application is implementing the duct anemometer in new and existing VAV boxes, where the anemometer would likely have most market penetration. To illustrate this application, Figure 33 shows a typical VAV box with reheat.

Figure 19: Typical Existing Variable Air Volume Box



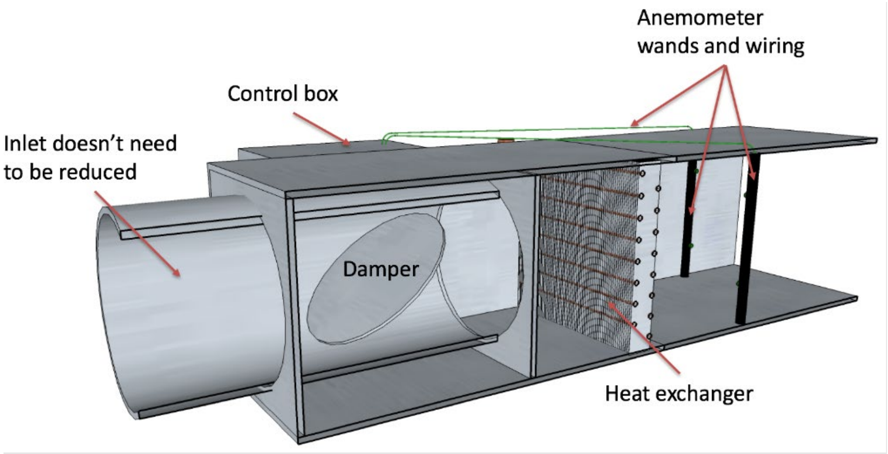
Schematic drawing of the inlet and existing flow measurement of a VAV box with reheat coil.

Source: Dove Feng, TRC

The typical VAV box has a constriction from the inlet duct to the box, solely to provide a pressure drop for the flow cross measurement; this "step-down" in duct size increases pressure drop and fan energy use. At low airflow rates (75 fpm or 0.4 m/s), the existing flow cross is not very accurate. Thus, in practice, designers use higher minimum flow set points, which results in over-ventilation and over-cooling, that in turn causes comfort issues and wasted energy.

By contrast, the sonic duct anemometer described in the project could allow a reconfiguration of the VAV box, shown in Figure 34.

Figure 20: Reconfiguration of a Variable Air Volume Box With New Sonic Duct Anemometer



Schematic drawing of a revised VAV box with reheat coil that uses the anemometer downstream.

Source: Dove Feng, TRC

In this new design, no step-down is required, which means less pressure loss, which in turn translates to lower fan energy use. In addition, the duct anemometer is highly accurate at low flow rates, allowing engineers and building operators to use lower minimum flow set points, resulting in reduced over-ventilation and provides better thermal comfort and reduces wasted energy. In summary, for these new VAV boxes, the benefits include:

Reduced supply fan design pressure due to less pressure loss at the terminal units with increased inlet duct size.

Reduced fan energy and VAV reheat energy as the minimum flow setpoint can be reduced to ventilation requirement

For existing VAV boxes, the duct anemometer could potentially replace the existing airflow cross such that the VAV box minimum flow setpoint could be reduced to the larger of ventilation requirement and controllable minimum.

Approach in Estimating Energy Savings

The estimation of the energy impacts used the prototype buildings developed by the Department of Energy, using a medium office, a large office, and a large school.

Key assumptions are listed:

Fan static pressure drop reduction: if the duct anemometers were used to replace the flow crosses, the total pressure drop across the VAV boxes could be reduced. Based on American Society of Heating, Air-Conditioning, and Refrigerating

Engineers duct fitting pressure loss database[8], the researchers estimated about 0.2-inch water column of pressure drop could be reduced by avoiding the transition to small VAV box inlet, and an additional 0.2-inch water column of pressure drop reduction through the system, including larger inlet duct and reduced system losses. In total, this translates to 0.4-inch water column of pressure drop for the supply fan.

For new VAV boxes, researchers estimated savings by reducing the minimum airflow setpoint from 20 percent to minimum ventilation rates.

For retrofit VAV boxes, researchers estimated savings by reducing minimum from 30 percent to minimum ventilation rates.

Table 1 shows the percentage HVAC electricity and gas savings. Assumptions include that college buildings include 80 percent classroom types and 20 percent offices; and the savings were estimated based on savings for office and school buildings. The researcher only estimated 5 percent savings for hospitals because the minimum flow requirements are highly regulated. The saving estimation for miscellaneous was calculated based on the average of the other building types.

Table 1: Saving Estimation for Various Building Types

Category		Small office	Large office	School	College	Health	Miscellaneous
HVAC Electricity Savings	Retrofit	12.5%	12.5%	9.0%	9.7%	5.0%	9.7%
	New	5.0%	5.0%	3.3%	3.3%	2.0%	3.7%
HVAC Gas Heating Savings	Retrofit	22.0%	22.0%	13.0%	14.8%	5.0%	15.4%
	New	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Source: Dove Feng, TRC

Assuming 15 percent final market penetration for new VAV applications, and 10 percent penetration for retrofit VAV boxes, the estimated total statewide savings is 265GWh/year and 38 million Therms/year. This equals annually to $90 million, and 226,000 metric tons of equivalent carbon dioxide. These figures are based upon an estimated level of market penetration 10 years from project end (a rate of approximately 1 to 2.5 percent of applicable buildings per annum, a rate of approximately 0.2 to 1.8 percent of the overall building stock in each category). Savings by building categories are outlined in Table 2.

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[8] American Society of Heating, Air-Conditioning, and Refrigerating Engineers duct fitting database.

https://www.ashrae.org/technical-resources/bookstore/duct-fitting-database

Table 2: Saving Estimation for Various Building Types

Category	Small office	Large office	School	College	Health	Miscellaneous	Total
HVAC electricity savings (Gwh)	18.2	133.2	9.6	12.7	25.7	66.1	265.5
HVAC gas savings (million Therms)	2.3	16.2	3.0	3.8	3.0	9.9	38.1

Source: Dove Feng, TRC

Next Steps

The team will continue to engage with potential manufacturers, especially Swegon and TSI. The researchers submitted one paper on the signal processing, and two other papers on each of the anemometers (Appendix D) to Institute of Electrical and Electronics Engineers. The team is developing videos for use in disseminating the technology. A provisional patent has been submitted for signal processing and anemometer configuration inventions; inventions apply to the room and duct anemometers.

The research team is seeking funding to continue testing and development of the room and duct anemometers (Figure 35). The team is building 100 anemometers for use in field testing, including testing the bipyramidal duct design, testing the CH-201 chips if possible, and testing the dust filter and the horns.

Figure 21: Building Multiple Room Anemometers for Field Testing

Battery-powered and USB-powered room anemometers are built and ready for testing.

Photo Credit: Hui Zhang, University of California, Berkeley

CHAPTER 7: Conclusion

Within buildings' occupied spaces, there is a widely unmet need for monitoring indoor air speed and direction for appraising and controlling: occupant cooling for comfort, physiological heat stress for occupational health and safety, pathogen dispersion, ventilation and air quality, energy flows in data centers, safety and energy alerts, and the operation of natural ventilation and ceiling fans.

Such monitoring should provide high resolution at low air velocities, occur within the airstream of interest, and—because stringing wires is expensive and intrusive—preferably have wireless connectivity and the ability to operate over a long period using a battery.

The current indoor anemometer devices (hotwire, impellers) are power-hungry or insensitive at low speeds. Most are not suitable for long-term unattended monitoring, because of their fragility or because their protective shielding makes them insensitive to certain wind directions. The few omnidirectional and three-dimensional devices extant are expensive research instruments. None provide a record of wind direction or the orientation of the instrument relative to the earth.

Within buildings' HVAC systems, there is a need for more accurate and ubiquitous monitoring of air flows in ducts, VAV boxes, outside air inlets, and fume hoods. Current monitoring takes place through devices that impose parasitic losses in the ventilation system, or are expensive arrays subject to fouling. An ideal monitor would be non-intrusive in the flow field and be sensitive to flows (and flow reversals) at low speeds. The monitors could be integrated with existing HVAC equipment or installed in the system as retrofits. Better assurance of the various flows through HVAC channels would make building operation far more energy efficient than current practice.

Recently developed micro-electromechanical systems ultrasonic transducers operating at high frequency have opened the opportunity for such indoor monitors, offering lower velocity thresholds, higher sensitivity at low speeds, small size of anemometer, directionality including multiple axes, low power, long monitoring life, and mass production potential.

Project Accomplishments

In this project, the research team has identified and characterized many of the mentioned anemometry needs and projected the benefits to building operation practice that would occur with the availability of improved air movement monitoring.

The research team has also successfully developed and tested two air flow sensors: an anemometer that measures air flow and direction for rooms, and an anemometer that measures the air flow within HVAC ducts. A description follows.

Both anemometers use high-frequency ultrasonic transceivers arranged to create a set of sonic pathways. Pulse signals are sent in both directions down each path, and the differences in their times-of-flight determine the wind velocity along the path. The time-of-flight is measured by the phase angle of a defined wave cycle within the pulse. The method is guided by a coincident temperature measurement. The signal processing represents a unique innovation in acoustic anemometry.

The anemometers include a built-in thermometer to supplement the sonic temperature measurements. They include a built-in 802.15.4 radio for wireless communication to a router/internet, and a built-in magnetic compass/tilt sensor to permit self-orientation relative to the earth's horizon and zenith.

The Room Anemometer

Uses a tetrahedron for minimizing the needed number of transceivers for three-dimensional flow definition (to four from six) and reducing wake effects along the sonic path between transceivers. The signals are sent in a one-pitch, three-catch arrangement, cycling through the four transceivers providing 12 times-of-flight along six paths; this is reduced to six delta times-of-flight for each cycle. The six paths provide redundancy over the three paths needed to define three-dimensional flow. The redundancy enables the inevitable wakes of anemometer support structure to be detected and eliminated from the air speed calculations. The room anemometer configuration and signal processing are also a unique contribution in the field.

The room anemometer's 6 cm path length allows high resolution at low speeds (<0,05m/s) and a top speed of 7 m/s, appropriate for most indoor airflow applications. It was developed in two USB-powered forms: 'Maximum' (support struts distant from the sonic paths to reduce wake and reflection effects), 'Minimum' (support struts close to keep the instrument as compact as possible), and a battery-powered 'Minimum' (in which the tetrahedron is elevated by distance required by a D-cell-sized lithium-ion battery.)

The Duct Anemometer

The duct anemometer carrier board will support a three-by-three arrangement of transceivers, but the researchers have only developed and tested a two-by-two version to date. Three configurations of the duct anemometer have been developed and studied: VAV box with/without terminal reheat coil, and a duct retrofit version. The configuration of the VAV box without coil may change, putting the anemometer upstream of the VAV damper while eliminating the circular flow constriction at the inlet of the box. These considerations will be evaluated by our manufacturing partner.

Maximum measurable duct size is a limitation with the current prototype (23 cm maximum path length between transceivers). Maximum measurable airspeed is variable, but is currently about seven m/s with the 175kHz CH-101 transceiver. The newly developed CH-201 at 80kHz would allow three times higher maximum speed and five times the range at the expense of some resolution at the lower end.

The researchers are looking for additional funding to continue the development and testing of the anemometers. The researchers will continue to pursue the bipyramid duct anemometer as well as the lower frequency CH-201 transceivers, both may allow higher air flow measurement up to 4000 fpm (20 m/s), improve accuracy, and use in larger ducts, which are necessary improvements to compete in the current market.

Technology and Knowledge Transfer

The research team submitted a patent application through UC Berkeley on April 8, 2020.

So far three journal papers have been published: two *IEEE* papers: one in IEEE Sensors journal, and one in IEEE Sensors 2020 Conference in Montreal, and an *Energy and Buildings* paper published March 2020.

Ghahramani, A., Przybyla, R. J., Andersen, M. P., Min, S., Peffer, T., Zhu, M., … Arens, E. (2019). An inexpensive low-power ultrasonic 3-dimensional air velocity sensor. IEEE Sensors Journal.

A. Ghahramani, R.J. Przybyla, M.P. Andersen, S. Min, T. Peffer, M. Zhu, H. Zhang, E. Arens. 2019. Measuring air speed with a low-power MEMS ultrasonic anemometer via adaptive phase tracking. IEEE Sens. J. June 2019. DOI: 10.1109/JSEN.2019.2920648.

Arens, Edward, Ali Ghahramani, Richard Przybyla, Michael Andersen, Syung Min, Therese Peffer, Paul Raftery, Megan Zhu, Vy Luu, Hui Zhang. 2020. Measuring 3D indoor air velocity via an inexpensive low-power ultrasonic anemometer. Buildings and Energy. Vol 211. https://doi.org/10.1016/j.enbuild.2020.109805

One Mutual NDA is in place with a major US anemometer manufacturer, and with a major international HVAC air-handling equipment manufacturer. Contacts with California manufacturers of anemometry and duct-airflow-measurement equipment will be reactivated when the team has a new duct-flow prototype tested. The MEMs transceiver manufacturer (Chirp Microsystems) has passed the startup stage and is now part of TDK, a Japanese manufacturer of memory media and other electronics. It maintains a California presence with approximately 30 employees performing research and development of ultrasonic MEMs device.

GLOSSARY AND ACRONYMS

Term	Definition
ASIC	Application Specific Integrated Circuit. For this project, the ASIC is the 3.5 mm transceiver with membrane that vibrates upon triggering with an electric signal.
EPIC (Electric Program Investment Charge)	The Electric Program Investment Charge, created by the California Public Utilities Commission in December 2011, supports investments in clean energy technologies that benefit electricity ratepayers of Pacific Gas and Electric Company, Southern California Edison Company, and San Diego Gas & Electric Company.
MEMS	Micro Electrical Mechanical Systems, using referring to techniques used in the semiconductor industry that develops mechanical components millimeters in size.
smart grid	Smart grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.
TOF	Time of flight refers to the interval of time it takes for a sonic pulse to travel from the sending to the receiving transceiver
VAV	Variable Air Volume

REFERENCES

Andersen, Michael P., John Kolb, Kaifei Chen, Gabe Fierro, David E. Culler, Raluca Ada Popa. 2017. WAVE: A Decentralized Authorization System for IoT via Blockchain Smart Contracts. University of California, Berkeley: Electrical Engineering Computer Science. Technical Report No. UCB/EECS-2017-234 http://www2.eecs.berkeley.edu/Pubs/TechRpts/2017/EECS-2017-234.html.

Arens E., S. Turner, H. Zhang, and G. Paliaga. 2009. Moving air for comfort. ASHRAE Journal, May 51 (25), 8 – 18. https://escholarship.org/uc/item/6d94f90b

Arens, E., H. Zhang, T. Hoyt, S. Kaam, F. Bauman, Y.C. Zhai, G. Paliaga, J. Stein, B. Tully, J. Rimmer, and J. Toftum. 2015. Effects of Diffuser Airflow Minima on Occupant Comfort, Air Mixing, and Building Energy Use (RP-1515). Science and Technology for the Built Environment 0,1-16.

Arens, E., H. Zhang, T, Hoyt, S. Kaam, J. Goins, F. Bauman, Y. Zhai, T.Webster, B. West, G. Paliaga, J. Stein, R. Seidl, B. Tully, J. Rimmer, and J. Toftum. 2012. Thermal air quality acceptability in buildings that reduce energy by reducing minimum airflow from overhead diffusers. Final report for ASHRAE RP-1515. https://escholarship.org/uc/item/3jn5m7kg

Arens, E., Zhang, H., Kim, D, Buchberger, E., Bauman, F., Huizenga, C., Higuchi, H. 2008. "Impact of a task-ambient ventilation system on perceived air quality." Indoor Air 2008, August 17-22, Copenhagen.

Arens, E., Ghahramani, A., Andersen, M. P., Zhang, H., Peffer, T., & Raftery, P. (2019). *Patent No. 62,830,993*. U.S. Provisional to University of California, Berkeley.

Arens, E., A. Ghahramani, M.P. Andersen, H. Zhang, T. Peffer, P. Raftery. 2019. Ultrasonic anemometers for sensing air flows in rooms and ducts, U.S. Provisional Patent to University of California, Berkeley, No. 62,830,993, 2019.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), 2018. ASHRAE Guideline 36-2018. High-Performance Sequences of Operation for HVAC Systems. Atlanta: American Society of Heating, Air-Conditioning, and Refrigerating Engineers, Inc.

ASHRAE, 2017. ASHRAE Standard 55-2017. Thermal environmental conditions for human occupancy. Atlanta: American Society of Heating, Air-Conditioning, and Refrigerating Engineers, Inc.

ASHRAE, 2016. ASHRAE Standard 62.1-2016. Ventilation for Acceptable Indoor Air Quality. Atlanta: American Society of Heating, Air-Conditioning, and Refrigerating Engineers, Inc.

ASHRAE, 2016. ASHRAE Standard 62.2-2016. Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. Atlanta: American Society of Heating, Air-Conditioning, and Refrigerating Engineers, Inc.

ASHRAE, 2017. ASHRAE Standard 90.1-2017. Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta: American Society of Heating, Air-Conditioning, and Refrigerating Engineers, Inc.

ASHRAE, 2013. ASHRAE Standard 195-2013. Method of Test for Rating Air Terminal Unit Controls. Atlanta: American Society of Heating, Air-Conditioning, and Refrigerating Engineers, Inc.

Brelih, N. (2012). How to improve energy efficiency of fans for air handling units. Retrieved May 29, 2020, from REHVA Journal website: https://www.rehva.eu/rehva-journal/chapter/how-to-improve-energy-efficiency-of-fans-for-air-handling-units

Ghahramani, A., Przybyla, R. J., Andersen, M. P., Min, S., Peffer, T., Zhu, M., … Arens, E. (2019). An inexpensive low-power ultrasonic 3-dimensional air velocity sensor. *IEEE Sensors Journal*.

Ghahramani, A., J. Pantelic, M. Vannucci, L. Pistore, S. Liu, B. Gilligan, S. Alyasin, E. Arens, 1028, Personal CO2 Bubble: Context-dependent Variations and Wearable Sensors Usability, Journal of Building Engineering, Online available, Nov. 2018

Guedes, A., S. Shelton, R. Przybyla, I. Izyumin, B. Boser, and D. Horsley. 2011. "Aluminum nitride pMUT based on a flexurally-suspended membrane," in Proc. Solid-State Sensors, Actuators and Microsystems Conference (TRANSDUCERS) 2011, pp.2062-2065, Beijing, China, 5-9 June 2011.

Han, D., Kim, S., & Park, S. (2008). Two-dimensional ultrasonic anemometer using the directivity angle of an ultrasonic sensor. *Microelectronics Journal*, *39*(10), 1195–1199. https://doi.org/10.1016/J.MEJO.2008.01.090

Högström, U., & Smedman, A.-S. (2004). Accuracy of Sonic Anemometers: Laminar Wind-Tunnel Calibrations Compared to Atmospheric In Situ Calibrations Against a Reference Instrument. *Boundary-Layer Meteorology*, *111*(1), 33–54. https://doi.org/10.1023/B:BOUN.0000011000.05248.47

Horst, T. W., Semmer, S. R., & Maclean, G. (2015). Correction of a Non-orthogonal, Three-Component Sonic Anemometer for Flow Distortion by Transducer Shadowing. *Boundary-Layer Meteorology*, *155*(3), 371–395. https://doi.org/10.1007/s10546-015-0010-3

Hoyt, T., E. Arens, and H. Zhang. 2014. Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. Building and Environment. doi:10.1016/j.buildenv.2014.09.010 https://escholarship.org/uc/item/13s1q2xc

Kaimal, J. C. (2013). *Advances in Meteorology and the Evolution of Sonic Anemometry*. Retrieved from http://www.apptech.com/wp-content/uploads/2016/08/Evolution-of-Sonic-Anemometry.pdf

Kanomax. (2017). Climomaster Anemometer Model 6501.

Kim, H.-S., Andersen, M. P., Chen, K., Kumar, S., Zhao, W. J., Ma, K., & Culler, D. E. (2018). System Architecture Directions for Post-SoC/32-bit Networked Sensors. *Proceedings of the 16th ACM Conference on Embedded Networked Sensor Systems - SenSys '18*, 264–277. https://doi.org/10.1145/3274783.3274839

Kochendorfer, J., Meyers, T. P., Frank, J. M., Massman, W. J., & Heuer, M. W. (2013). Reply to the Comment by Mauder on "How Well Can We Measure the Vertical Wind Speed? Implications for Fluxes of Energy and Mass." *Boundary-Layer Meteorology*, *147*(2), 337–345. https://doi.org/10.1007/s10546-012-9792-8

Lecamwasam, L., Wilson, J., & Chokolich, D. (2012). *Guide to Best Practice Maintenance & Operation of HVAC Systems for Energy Efficiency* (H. V. & A.-C. H. E. S. S. C. of A. G. (COAG) N. S. on E. Efficiency, Ed.). Retrieved from http://climatechange.gov.au/http://creativecomons.org/licenses/by/3.0/au/.

Mauder, M., & Zeeman, M. J. (2018). Field intercomparison of prevailing sonic anemometers. *Atmospheric Measurement Techniques*, *11*(1), 249–263. https://doi.org/10.5194/amt-11-249-2018

Omega. (n.d.). Laboratory Grade Benchtop Wind-Tunnel with Instrumentation | Omega Engineering. Retrieved May 23, 2019, from https://www.omega.com/en-us/calibration-equipment/wind-tunnels/p/WT4401

PlantPro. (2016). Making your plant room a value-generating asset. Retrieved May 29, 2020, from AutomatedBuildings.com website: http://automatedbuildings.com/news/jun16/articles/plantpro/160517014202plantpro.html

Przybyla, R., S. Shelton, A. Guedes, R. Krigel, D. Horsley, and B. Boser. 2012. "In-air Ultrasonic Rangefinding and Angle Estimation using an Array of AlN Micromachined Transducers," in Proc. Hilton Head Solid-State Sensors, Actuators and Microsystems Workshop 2012, 3-7 June 2012, pp. 50-53.

Przybyla, R. 2013. "Ultrasonic 3D Rangefinder on a Chip," Ph.D. Dissertation, University of California, Berkeley, CA, December 2013.

Przybyla, R., H.-Y. Tang, S. Shelton, D. Horsley, and B. Boser. 2014. "3D Ultrasonic Gesture Recognition," in Proc. International Solid State Circuits Conference 2014, San Francisco, CA, 9-13 February 2014.

Przybyla, R., H.-Y. Tang, S. Shelton, A. Guedes, D. Horsley, and B. Boser. 2015. "Ultrasonic 3D Rangefinder on a Chip," Journal of Solid State Circuits, vol. 50, no. 1, pp.320-334, January 2015.

Przybyla, R. J., Shelton, S. E., Guedes, A., Izyumin, I. I., Kline, M. H., Horsley, D. A., & Boser, B. E. (2011). In-Air Rangefinding With an AlN Piezoelectric Micromachined Ultrasound Transducer. *IEEE Sensors Journal*, *11*(11), 2690–2697. https://doi.org/10.1109/JSEN.2011.2157490

Przybyla, R. J., Tang, H.-Y., Guedes, A., Shelton, S. E., Horsley, D. A., & Boser, B. E. (2015). 3D Ultrasonic Rangefinder on a Chip. *IEEE Journal of Solid-State Circuits*, *50*(1), 320–334. https://doi.org/10.1109/JSSC.2014.2364975

Sensor Electronic. (n.d.). SensoData5500. Retrieved May 23, 2019, from http://www.sensor-electronic.pl/

Shelton, S., M.-L. Chan, H. Park, D. Horsley, B. Boser, I. Izyumin, R. Przybyla, T.Frey, M. Judy, K. Nunan, F. Sammoura, and K. Yang. 2009. "CMOS-compatible AlN piezoelectric micromachined ultrasonic transducers," in Proc. IEEE Ultrasonics Symp. 2009, Oct. 2009, pp. 402-405.

Shelton, S., O. Rozen, A. Guedes, R. Przybyla, B. Boser, and D. Horsley. 2012. "Improved acoustic coupling of air-coupled micromachined ultrasonic transducers," in Proc. IEEE MEMS 2014, 26 January 2012, pp. 753-756.

Shelton, S., A. Guedes, R. Przybyla, R. Krigel, B. Boser, and D. Horsley. 2012. "Aluminum Nitride Piezoelectric Micromachined Ultrasound Transducer Arrays," in Proc. Hilton Head Solid-State Sensors, Actuators and Microsystems Workshop 2012, 3-7 June 2012, pp. 291-294.

Sonic Corporation. (n.d.). *Measurement of 3-Dimensional Wind Velocity Components*. Retrieved from http://www.u-sonic.co.jp/english

TSI. (n.d.). Thermal Anemometry Probes 1210-10 -. Retrieved May 23, 2019, from https://www.tsi.com/product-components/thermal-anemometry-probes-1210-10/

Wieser, A., Fiedler, F., Corsmeier, U., Wieser, A., Fiedler, F., & Corsmeier, U. (2001). The Influence of the Sensor Design on Wind Measurements with Sonic Anemometer

Systems. *Journal of Atmospheric and Oceanic Technology*, *18*(10), 1585–1608. https://doi.org/10.1175/1520-0426(2001)018<1585:TIOTSD>2.0.CO;2

Zhai, Y., C. Elsworth, E. Arens, H. Zhang, Y. Zhang, and L. Zhao. 2015. Using air movement for comfort during moderate exercise. Building and Environment, 94, 344-352

Zhai, Y., Y. Zhang, H. Zhang, W. Pasut, E. Arens, and Q. Meng. 2015. Thermal comfort and perceived air quality with ceiling fans in warm-humid conditions. Building and Environment, 90: 178 – 185.