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An on-site computer system for comprehensive agricultural air quality research☆

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ABSTRACT

Scientific studies using direct agricultural air quality (AAQ) measurement have experienced revolutionary changes since such a study was first reported in the early 1950s. Comprehensive AAQ research with multi-institutional or international collaboration, long-term monitoring, and multi-pollutant measurement has been conducted with greater frequency. On-site computer system (OSCS), consisting of data acquisition hardware, a personal computer, and custom-developed AAQ research software has become an important tool in these studies. The role of the OSCS has been expanded from exclusively data acquisition to a combination of data acquisition, control, regular and advanced data processing, and communication. This paper studied the general and specific requirements of OSCS in AAQ research and introduced a system with new methodology and technology for high level quality assurance and quality control (QAQC).

Data acquisition in AAQ studies is needed for five main categories of instruments and sensors: pollutant concentrations, air exchange, weather conditions, building status, and measurement system status. Regular data processing consists of converting electrical signals to engineering units, averaging data over a given period of time, and performing data correction. Advanced data processing includes calculating location-shared analyzers and sensors (LSAS) data and instrument calibration data and generating daily reports in real-time or upon user requests. The primary control needs in AAQ research centers around the LSAS using multi-point air sampling system. Controls for sampling tubing heating and equipment cooling are often required. Computer communications to monitor system status, deliver alarms and data, and provide remote diagnosis and controls help to reduce operation costs and increase research quality and data completeness.

An OSCS that offered flexibility, high capacity, user-friendliness, and high level QAQC was developed for field and laboratory AAQ research. A total of 29 OSCSs have been built and used in various AAQ studies in 13 states in USA for handling a total of more than 3.0 billion data points. The system adapted a set of data processing algorithms as well as some novel features, including All-data Display and Dynamic Run-time Configuration (DDRC), Digital Output DDRC, real-time sampling system monitoring and protection, Global Channel, traceable configuration, and post-measurement data processing. The system also integrated two stand-alone instruments, an Innova multi-gas analyzer and a 7-port Environics gas diluter, which are popular in AAQ research. The strengths, weaknesses, and future development of the system are also discussed.

1. Introduction

Experimental study of agricultural air quality is critical to obtaining first-hand data for baseline emission determination, pollution impact assessment, modeling, and mitigation technology development. These studies employ measurement devices to obtain data directly from laboratory or field setups. The first reported agricultural air quality (AAQ) research using ammonia (NH_3) concentration measurement was conducted in the beginning of the 1950s in Ohio, USA (Cotterill and Winter, 1953). Early studies in this field only depended on limited numbers of discrete samples and small quantities of data. In the past five decades, remarkable development has been witnessed in terms of monitoring scale, measurement duration, pollutants investigated, and technology advancement in this field. Multi-institutional or international projects have been reported (e.g., Phillips et al., 1998; Liang et al., 2005; Heber et al., 2008; Moody et al., 2008). Monitoring time has increased from several days or weeks to more than 2 years to span across animal and bird growth cycles, manure accumulations, and seasonal variations of air quality. Pollutants investigated now include gases, particulate matter, odour, volatile organic compounds (VOC), and pathogens.

Technology advancement in analytical instruments, computers, and electronics has revolutionized the capability of AAQ research.

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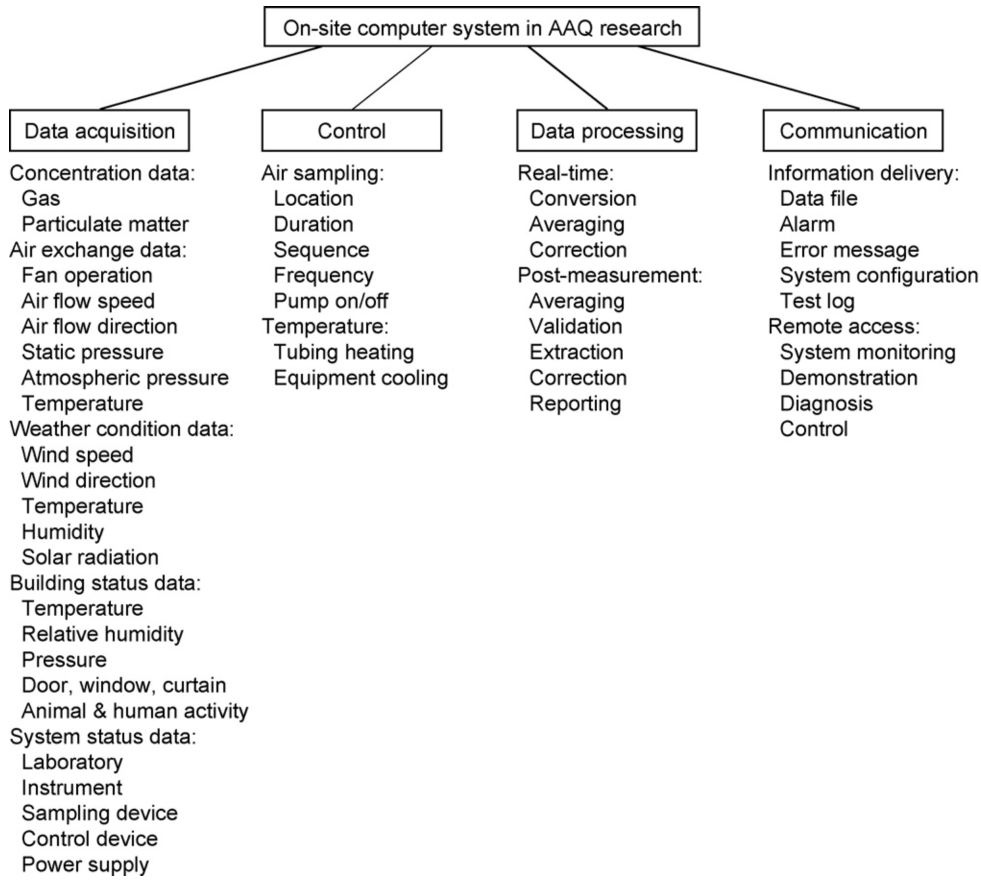


Fig. 1. General and advanced features of on-site computer system in agricultural air quality research.

Today, comprehensive AAQ research, whether in field or laboratory conditions, often utilizes multiple on-line instruments and sensors for long-term monitoring of longer than 6 months to cover seasonal variations. Automatic control of sampling devices is also widely used. Some of these research projects involved millions of dollars and the average cost of obtaining 1 day worth of data at one measurement site often exceeded US$ 1000. Failures of instruments, devices, hardware, and software often cause loss of data. Contrarily, reliable and powerful methodology, technology, and research tools can reduce setup and operational costs, increase data completeness, and enhance project quality assurance and quality control (QAQC).

On-line measurement in AAQ research requires computer-aided data acquisition to handle large quantities of data at high frequency. The on-site computer system (OSCS), installed at the measurement site and consisting of data acquisition and control hardware, a personal computer, and AAQ research-specific software, therefore becomes an important research tool. The main function of the OSCS has been data acquisition. Although descriptions of data acquisition systems in various agricultural research fields were published (e.g., Xin et al., 1994; Al-Janobi, 2000), little information about these systems specifically for AAQ research is available in the literature. The first paper that provided detailed descriptions of such a system was published more than three decades ago by Feddes and McQuitty (1977). Some recent publications mentioned data acquisition software written in LabVIEW (National Instruments Corporation, Austin, TX) in AAQ research, but no details were included (e.g., Moody et al., 2008).

The complexity of modern comprehensive AAQ research has expanded the requirements of OSCS to multiple tasks. Reliable, powerful, and user-friendly OSCS can assure research quality and facilitate quality control by increasing measurement accuracy, improving data completeness, enhancing research documentation, and reducing human errors. It can boost work efficiency not only during the laboratory and field measurements, but also in subsequent research data processing. In addition, it can significantly reduce costs of measurement system development and operation. So far there is no commercial OSCS specifically developed for comprehensive AAQ research. Although various air quality studies involve similar objectives and instrumentation, they usually require that the OSCS be set up and software be developed from scratch or modified substantially from existing systems at the start of a project (Phillips et al., 1998; Heber et al., 2001).

An OSCS developed only for individual projects has several drawbacks. Because of insufficient time and resources, the resulting system usually only satisfies the specific project objective and lacks user-friendly flexibility for hardware modification and software configuration. The work load for post-experimental data processing in AAQ research can be substantial because the OSCS usually cannot provide effective and efficient QAQC features. Additionally, the development of the OSCS, especially the software, is a very time-consuming and expensive process. It can be a significant part of the project cost. Therefore, a user-friendly OSCS with powerful features for high level QAQC is beneficial for the growing number of comprehensive AAQ studies. Ni et al. (2009) reviewed historical development of AAQ projects and briefly introduced a new OSCS in this research field. However, more details about the system need to be presented and discussed so that users of computers and electronics in agriculture can build similar systems and make further improvements.

The objectives of this article are to:

1. Identify general and specific requirements of OSCSs in AAQ research.
2. Present detailed descriptions of the new OSCS, including its real-time data processing algorithms and other novel features, for comprehensive AAQ studies.

2. On-site computer systems in agricultural air quality research

2.1. Overview of system requirements

The basic task of traditional OSCS in AAQ research is data acquisition. However, more complex and advanced tasks are needed in modern AAQ research for multi-institutional and international projects with long-term measurement, multi-point sampling, and multi-pollutant monitoring. The systems in these projects have been expanded from data-acquisition-only to a combination of data acquisition, control, data processing, and communication (Fig. 1). While satisfying the general requirements of AAQ research, an advanced OSCS is also desired to be easily applicable to different projects, have capacity for high level QAQC in large AAQ studies, be user-friendly, and integrate some important stand-alone devices.

2.1.1. Data acquisition

The purpose of data acquisition is to acquire electronic signals from various on-line measurement and monitoring devices to the computer. The measurement of air pollutant concentrations using analytical instruments and sensors is essential to all experimental AAQ studies. If pollutant emissions are of interest to the projects, air exchange rates must be measured directly or indirectly. Weather conditions are almost always included in comprehensive AAQ research, especially when they involve naturally ventilated animal barns, manure storages, and lagoons. Monitoring building status is often included in emission studies at mechanically ventilated or naturally ventilated buildings. The status of measurement system also needs to be monitored to ensure that all instruments and sensors are working at normal environmental conditions.

2.1.2. Control

The main control purpose of these systems is to satisfy one of the distinguishing characteristics in AAQ research: multi-point sampling using location-shared analyzers and sensors (LSAS). This method employs a single set of analyzers and sensors for measuring air samples transported via multiple pieces of tubing radiated to different locations using a sampling system. It has been in practice since the 1970s (Feddes and McQuitty, 1977) and widely used in Europe and North America (e.g., Berckmans and Ni, 1993; Phillips et al., 1998; Heber et al., 2008; Moody et al., 2008). Sampling control allows the LSAS to measure the air from different locations one after another. Comprehensive sampling control also includes options for selecting sampling sequences within a group of locations, sampling duration at each location, and sampling frequency of each location relative to other locations. The computer system also closely monitors the status of air sampling operation, e.g., sampling pressure and sample airflow rate. Temperature control for cooling the equipment and instruments and for heating the sample transportation tubing to prevent condensation in sampled air is often needed to maintain favourable working conditions. On-off controls normally can satisfy all control purposes in these studies.

2.1.3. Data processing

Data processing can be performed real-time or post-measurement. Real-time data processing includes converting electrical signals to engineering units and averaging the values over a given period of time. It can also include correcting data based on instrument or sensor calibration, averaging data with special algorithms (e.g., for wind direction calculation), and processing LSAS and calibration data. Post-measurement data processing performed automatically on a daily basis is desired because the previous-day measurement results can then be provided for quick feedback of test results. It can include reports with tables and graphs of daily raw data as well as extracted, validated, and averaged data. Extraction and validation are needed for LSAS data and instrument calibration data. Data graphs are extremely useful for visual inspection to quickly identify measurement problems.

2.1.4. Communication

Communication is the delivery of information, including data and configuration files, alarms, error messages, and test logs by OSCS to researchers and the access to the OSCS by research personnel to perform remote system monitoring, diagnosis, and control mainly via internet. Because the monitoring system is often unattended in long-term AAQ studies, to timely and automatically inform research staff about system status, to send acquired or processed data, and to allow remote accessing are desired features in advanced OSCS.

2.1.5. Applicability

Although it is nontrivial to develop an OSCS that is one-size-fits-all, it is important that such a system be readily applicable to different AAQ studies that have similar objectives and use comparable instruments and sensors. In addition, it should be readily adaptable to add-on projects that often occur in comprehensive field studies.

2.1.6. Capacity

Because of the increasing scope of AAQ research, the system should have the capacity to acquire large numbers of data at high frequency. It should be able to accept different data acquisition hardware, measurement instruments and sensors, and control devices. Dynamic real-time analog and digital configurations, remote diagnosis and control, and automation are also highly desirable.

2.1.7. User-friendliness

An advantageous user interface can provide easy monitoring, control, and configuration of the system. A user-friendly interface decreases time needed for training and operation, reduces errors caused by human operations, and increases efficiency of system checks and re-configurations.

2.1.8. Integration of stand-alone instruments and devices

Some advanced on-line-stand-alone instruments and devices store measurement data at manufacturer-defined formats and data-saving intervals with timestamps provided by the instrument internal clock in built-in data loggers. Although the data can be downloaded to the on-site computer via serial communication or memory card readers, the format and data-saving intervals are usually different from the OSCS. The timestamps from the devices and from the computer cannot be guaranteed to match due to clock deviation. These data usually also increase work load during post-measurement data processing because they must be matched with data from other instruments and sensors if they are a subset of the AAQ research measurement data. Integration of the important instruments and devices so that their data are saved in real-time

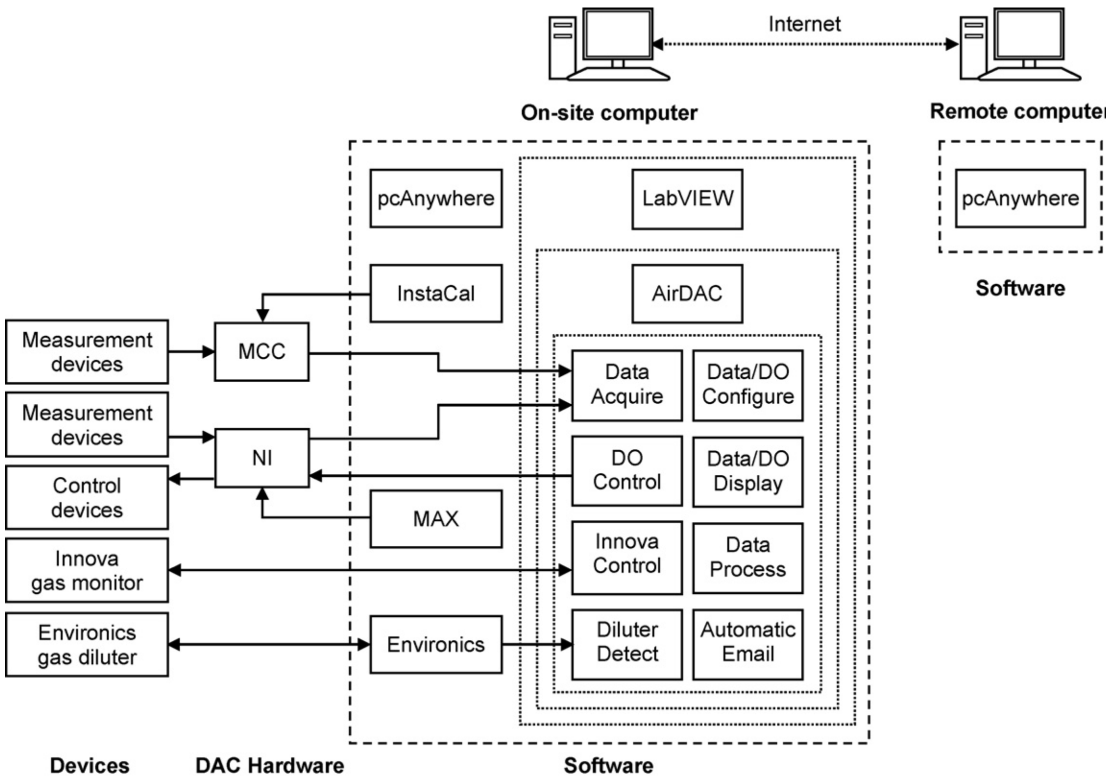


Fig. 2. Diagram of the new on-site computer system, consisting of an on-site computer, DAC hardware, and air quality research-specific software for data acquisition, digital output (DO) control, data processing, and communication.

into a single data file with all other instruments and sensors reduces costs and increases research QAQC.

2.2. Instruments, sensors, and other devices

Five groups of instruments and sensors are generally used in AAQ research (Fig. 1). They measure or monitor pollutant concentrations, air exchanges, weather conditions, building status, and measurement system status.

2.2.1. Concentration measurement instruments

There has been increasing use of on-line instruments to determine pollutant concentrations. Gas analyzers for ammonia (NH_3), hydrogen sulfide (H_2S), and carbon dioxide (CO_2) concentrations have been in use since the 1970s (Feddes and McQuitty, 1977). In the 1990s, on-line measurement also started for methane (CH_4), non-methane hydrocarbons, and nitrous oxide (N_2O) (Williams, 1993; Hoy and Kuhnel, 1995). On-line particulate matter measurement instruments, such as the Tapered Element Oscillating Microbalance (TEOM), have been employed in this field in recent years (Heber et al., 2006). However, on-line and real-time odour measurement instruments for AAQ research are not yet widely available.

2.2.2. Air exchange measurement sensors

Air exchange rate is as important as pollutant concentration when the research objective is to determine pollutant emission rate, which is the product of pollutant concentration and air exchange rate. For mechanically ventilated barns, various sensors for direct measurement of air flow rate, indirect measurement of air velocity, and monitoring of fan rotational speed or on/off status are used (Hoff et al., 2009). For naturally ventilated buildings, on-line anemometers are used for monitoring air flow speed and direction (Heber et al., 2008).

2.2.3. Weather monitoring sensors

Weather monitoring in AAQ research uses typical meteorological sensors for wind speed, wind direction, solar radiation, temperature, and relative humidity (Feddes and McQuitty, 1977). Ultrasonic wind direction and wind speed sensors are in increasing use in AAQ research.

2.2.4. Animal building status monitoring sensors

Sensors to measure differential pressure, temperature, relative humidity, and activity of animals and workers are common for monitoring building status in AAQ research. These sensors are used at multiple locations when large scale commercial animal buildings are monitored. Displacement sensors to monitor door openings, manure depths and curtain movements are sometimes needed.

2.2.5. Measurement system monitoring sensors

Sample airflow rate and pressure are the most important variables to monitor the operation of multiple-point sampling system (Heber et al., 2008). Occasionally, airflow direction sensors are needed to ensure that there is sufficient sample air provided to gas analyzers. Room temperature, humidity, and electric power supply are often monitored in instrument shelters.

2.2.6. Control devices

Solenoids are the main devices in AAQ research for controlling sampling air streams (Feddes and McQuitty, 1977; Heber et al., 2008; Moody et al., 2008). Cooling fan control is needed for certain enclosures where dissipated heat from pumps or other devices is a concern. Sampling air in transportation tubing should be kept warm enough to prevent condensation. Therefore, sampling tubing passing through cold zones is usually heated by heating tapes, of which the temperature should be controlled by the OSCS.

Table 1
Data acquisition hardware and integrated devices in AirDAC.

Manufacturer and model	I/O type	Number of channels	Note
National Instruments Co.			
FP-AI-112	Analog input	16	Single-ended, 16-bit
FP-AI-110	Analog input	8	Single-ended, 16-bit
FP-TC-120	Thermocouple input	8	
FP-DO-401	Digital output	16	2 A at 10–30 VDC
USB to RS485 4-port converter	Serial communication	496	Four channels for each 3D ultrasonic wind sensor for up to 124 sensors
Measurement Computing Co.			
USB AI 1600FS	Analog input	8 or 4	Eight single-ended or four differential, 16-bit
USB TC	Thermocouple input	8	
USB Temp	Multiple temperature sensor input	8	
USB 4303 counter	Count input	10	
USB DIO 96 H	Digital input	96	
USB miniLab	Analog input	8	Single-ended, 12-bit
	Digital input	32	Thirty-two with a connector board
LumaSense Technologies A/S			
Gas monitor 1314 or 1412	Serial communication	6	For six gases
Environics, Inc.			
Gas Diluter 4040	Serial communication	2	For gas # and concentration

3. A new on-site computer system

An OSCS system was developed by the Department of Agricultural and Biological Engineering (ABE), Purdue University, USA for comprehensive field and laboratory AAQ research. It consists of commercial data acquisition hardware, a personal computer, and custom-developed AAQ research software, AirDAC (Fig. 2). It implements new methodology to achieve high level QAQC. This OSCS also uses commercial software pcAnywhere (www.symantec.com) for remote accessing and controlling via Internet connection.

3.1. Data acquisition hardware and integrated devices

The system uses data acquisition hardware products from NI (National Instruments, Austin, TX) and MCC (Measurement Computing Corporation, Norton, MA). One or more FieldPoint banks from NI, each containing up to nine selectable modules, are connected to the on-site computer via Ethernet cables. FieldPoint modules for analog inputs, thermocouples, and digital outputs are the most commonly needed in AAQ research (Table 1).

Some devices from NI and MCC are connectable to the computer via USB ports. They include a variety of modules for serial communication, analog I/O, digital I/O, and counting. These devices are relatively easy to setup and configure and satisfy the general requirements of AAQ research.

The multi-gas monitor (Innova Models 1314 or 1412, LumaSense Technologies A/S, Ballerup, Denmark) and the 7-port gas diluter (Model 4040, Environics, Inc., Tolland, CT) for gas analyzer calibration are integrated into the OSCS.

3.2. Software

The software, AirDAC, consists of three separated but related programs, AirDAC Start, AirDAC Main, and Project-specific Display. The three programs are written in LabVIEW (NI), which is a graphical development environment with built-in functionality for data acquisition, instrument control, measurement analysis, and data presentation (Elliotta et al., 2007).

3.2.1. AirDAC Start

AirDAC Start is designed for users to initialize the system by setting up the project identification (ID), configuring data acquisition hardware, and selecting integrated devices, a configuration file, and a project-specific display program. The project ID, composed of one to four letters and numbers, is used by AirDAC to compose the names of automatically generated electronic files and the subjects of automatic emails. When USB-RS485 converter (NI) is selected for serial data acquisition, addresses of the sensors connected to the USB-RS485 converter can also be configured. Once the configurations are made, they are appended into a text file with a timestamp to document all configurations used in the project. The latest record is retrieved by AirDAC Start each time the program runs to perform data acquisition tasks.

3.2.2. AirDAC Main

AirDAC Main acquires all instruments/sensors signals, performs data processing, controls digital outputs, saves data to the computer hard drive, monitors system performance, delivers alarms, 1-min data, and electronic files via emails, and performs advanced post-measurement data processing (Fig. 3). It also writes all calculated data every second to memory via data sockets or global variables in LabVIEW for real-time project-specific display. AirDAC provides a six-tab front panel as user interface for integrated devices, measurement history graphs, All-data Display and Dynamic Run-time Configuration (DDRC), Digital Output DDRC, system monitoring and control, and a test notepad.

3.2.3. Project-specific display

AirDAC provides an optional display for project-specific monitoring. The project-specific display program reads the real-time data that are updated every second by AirDAC Main and presents them in front panels with a visual background of the project setup (e.g., animal house photos or lab test installation). It provides a more direct sense to the status of the system than the data shown in tables and graphs. This feature is especially beneficial for demonstrations and visitors.

3.3. Algorithms for data processing

Data processing algorithms adopted in AirDAC are based on characteristics of the measurement devices in AAQ research. They are programmed in AirDAC to convert acquired electric signals into related values in engineering units and to process the converted data based on specific requirements for each measurement variable. AirDAC performs these data processing steps in real-time.

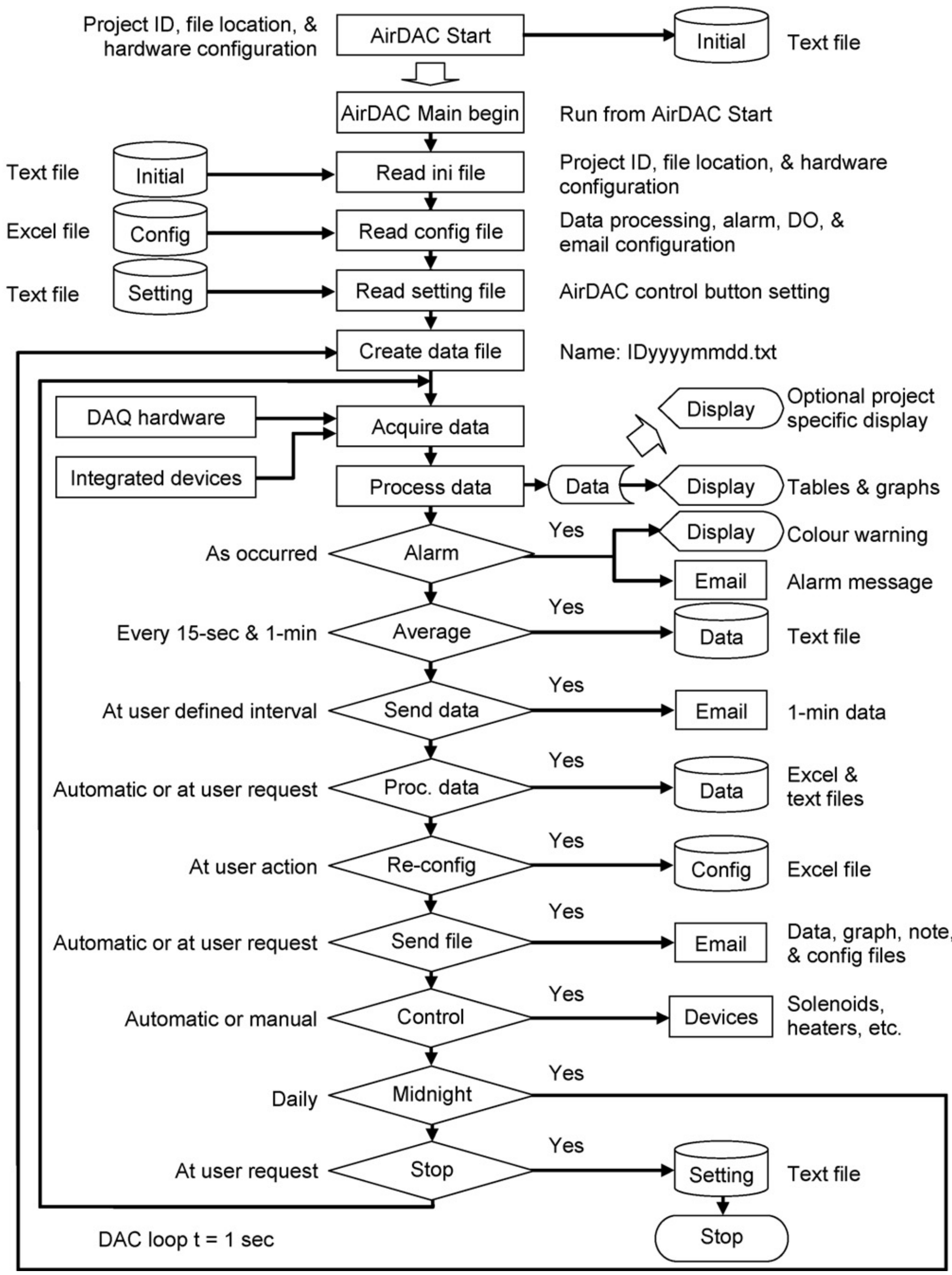


Fig. 3. Flow diagram of AirDAC Start, AirDAC Main, and optional project-specific display programs.

3.3.1. Data conversion

Analog signal outputs from commercialized analyzers and sensors, either in voltage or in current, are normally linear and have fixed or user-selectable signal ranges (e.g., from 0 to 10 VDC or from 4 to 20 mA). Analyzers and sensors also have fixed or user-selectable measurement ranges corresponding to the signal ranges (e.g., 0 VDC = 0 ppm and 10 VDC = 100 ppm for an ammonia analyzer).

AirDAC uses a generalized equation (Eq. (1)) to convert analog, digital, thermocouple, integrated instruments, and counter signals from each measurement device:

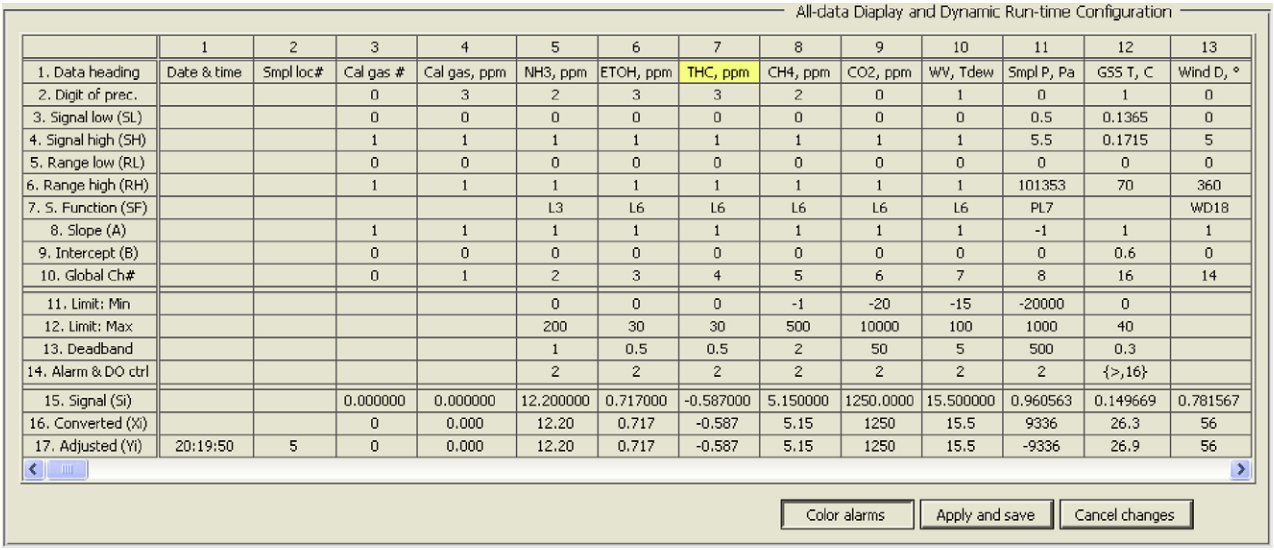
$$X_i = \frac{(S_i - S_L) \cdot (R_H - R_L)}{S_H - S_L} + R_L \tag{1}$$

where X_i is the converted ith measurement value, units defined by the measurement devices; S_i is the device output ith signal received by AirDAC, units in VDC, A, or defined by the measurement devices; S_H is the device signal range at high end, units in VDC, A, or dimensionless; S_L is the device signal range at low end, same units as S_H; R_H is the device measurement range at high end, units defined by the devices or dimensionless; R_L is the device measurement range at low end, same units as R_H.

The parameters S_H, S_L, R_H, and R_L are user-configurable at run-time for each individual instrument and sensor.

3.3.1.1. Thermocouple, integrated instrument, and rotational sensor signals. Signals from thermocouple outputs are already converted to temperature units in the NI or MCC data acquisition firmware. Therefore, their conversion parameters in AirDAC is set as $S_H = 1$, $S_L = 0$, $R_H = 1$, and $R_L = 0$ that are all dimensionless. With this configuration, Eq. (1) is reduced to Eq. (2):

$$X_i = S_i \tag{2}$$


All-data Diaplay and Dynamic Run-time Configuration

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Data heading	Date & time	Smpl loc#	Cal gas #	Cal gas, ppm	NH3, ppm	ETOH, ppm	THC, ppm	CH4, ppm	CO2, ppm	WV, Tdew	Smpl P, Pa	GSS T, C	Wind D, °
2. Digit of prec.			0	3	2	3	3	2	0	1	0	1	0
3. Signal low (SL)			0	0	0	0	0	0	0	0	0.5	0.1365	0
4. Signal high (SH)			1	1	1	1	1	1	1	1	5.5	0.1715	5
5. Range low (RL)			0	0	0	0	0	0	0	0	0	0	0
6. Range high (RH)			1	1	1	1	1	1	1	1	101353	70	360
7. S. Function (SF)					L3	L6	L6	L6	L6	L6	PL7		WD18
8. Slope (A)			1	1	1	1	1	1	1	1	-1	1	1
9. Intercept (B)			0	0	0	0	0	0	0	0	0	0.6	0
10. Global Ch#			0	1	2	3	4	5	6	7	8	16	14
11. Limit: Min					0	0	0	-1	-20	-15	-20000	0	
12. Limit: Max					200	30	30	500	10000	100	1000	40	
13. Deadband					1	0.5	0.5	2	50	5	500	0.3	
14. Alarm & DO ctrl					2	2	2	2	2	2	2	{>,16}	
15. Signal (Si)			0.000000	0.000000	12.200000	0.717000	-0.587000	5.150000	1250.0000	15.500000	0.960563	0.149669	0.781567
16. Converted (Xi)			0	0.000	12.20	0.717	-0.587	5.15	1250	15.5	9336	26.3	56
17. Adjusted (Yi)	20:19:50	5	0	0.000	12.20	0.717	-0.587	5.15	1250	15.5	-9336	26.9	56

Color alarms | Apply and save | Cancel changes

Fig. 4. AirDAC interface for All-data DDRC with a partial example configuration. Rows 1 through 14 are run-time configurable. Rows 15 through 17 are displays. The yellow-coloured cell "THC, ppm" is a visual alarm.

Similarly, the integrated instruments also provide converted outputs and should be configured the same as thermocouples as shown in columns 3–10 in Fig. 4. Rotational sensors should use Eq. (2) as well.

3.3.1.2. Binary signals. For sensors that have "on" and "off" binary outputs, AirDAC converts the "on" status signal to 100 and the "off" status signal to 0 before using Eq. (1). The conversion setting for binary output sensors is the same as for thermocouples. The converted sensor outputs have units in percent of time on (% t).

Eq. (1) can also be used to reverse the "on/off" digital sensor signals (e.g., convert the 0 as "on" and 100 as "off"). In this case, the parameters are set as $S_H = 1$, $S_L = 0$, $R_H = 0$, $R_L = 0$, $A = -1$ and $B = 100$.

3.3.1.3. Pulse signals. For rotational speed sensors with high frequency pulse signals that are acquired via counters, AirDAC converts the pulses into rotational frequencies with Eq. (3) before using Eq. (2):

$$S_i = 60\frac{C_i - C_{i-1}}{t_i - t_{i-1}} \tag{3}$$

where S_i is the converted ith measurement value, r/min (revolutions per min); C_i is the acquired ith count, revolution; C_{i-1} = acquired $(i-1)$th count, revolution; t_i is the absolute time when acquiring ith count, s; t_{i-1} is the absolute time when acquiring $(i-1)$th count, s.

3.3.2. Data correction

For any analyzers and sensors whose converted values need to be corrected or adjusted using a linear model (e.g., correcting analyzer outputs based on analyzer calibration or converting the temperature from °C to °F), Eq. (4) is applied in AirDAC for each sensor:

$$Y_i = A \cdot X_i + B \tag{4}$$

where A is the slope; B is the intercept.

Both A and B are also user-configurable at run time.

3.3.3. Data averaging

AirDAC averages the corrected or converted data to 15- and 60-s means with Eq. (5):

$$Y = \frac{1}{n}\sum_{i=1}^{n} Y_i \tag{5}$$

where Y is the mean of Y_i. Y is saved in data files; n is the number of samples ($n = 15$ for 15-s data file and $n = 60$ for 60-s data file).

For sensors with binary output signals, the value Y represents % of time that the sensor is "on". For example, $Y = 50$ in the 60-s data file means that the sensor is "on" for 30 s and "off" for 30 s, while in 15-s file it means that the sensor is "on" for 7.5 s and "off" for 7.5 s. Using the unit of % of time allows data to be further averaged without introducing errors compared with using the duration of time in seconds or minutes.

3.3.4. Special data processing

3.3.4.1. Wind direction sensor signal. Wind direction is a circular function with values between l and 360° after data processing using Eqs. (1) and (4). The wind direction discontinuity at the beginning and end of the scale requires a special algorithm to compute a valid mean value. A single-pass procedure was recommended by Bennett et al. (1999). The method assumes that the difference between successive wind direction samples is less than 180°; to ensure such, a sampling rate of once per second or greater should be computed the scalar mean wind direction.

AirDAC processes the 1 Hz wind direction data when averaging n samples ($n = 15$ or 60) using Eq. (6) from Bennett et al. (1999) before they are saved in data files:

$$Y = \frac{1}{n}\sum_{i=1}^{n} D_i \tag{6}$$

where $D_i = Y_i$, for $i = 1$; $D_i = D_{i-1} + \delta_i + 360$, for $\delta_i < -180$ and $i > 1$; $D_i = D_{i-1} + \delta_i$, for $|\delta_i| < 180$ and $i > 1$; $D_i = D_{i-1} + \delta_i - 360$, for $\delta_i > 180$ and $i > 1$; D_i is undefined for $\delta_i = 180$ and $i > 1$; $\delta_i = Y_i - D_{i-1}$, for $i > 1$; Y_i is the wind direction azimuth angle for the ith sample from Eq. (4).

3.3.4.2. Activity sensor signal. Signals from activity sensors require special processing because they have an offset voltage and the sen-

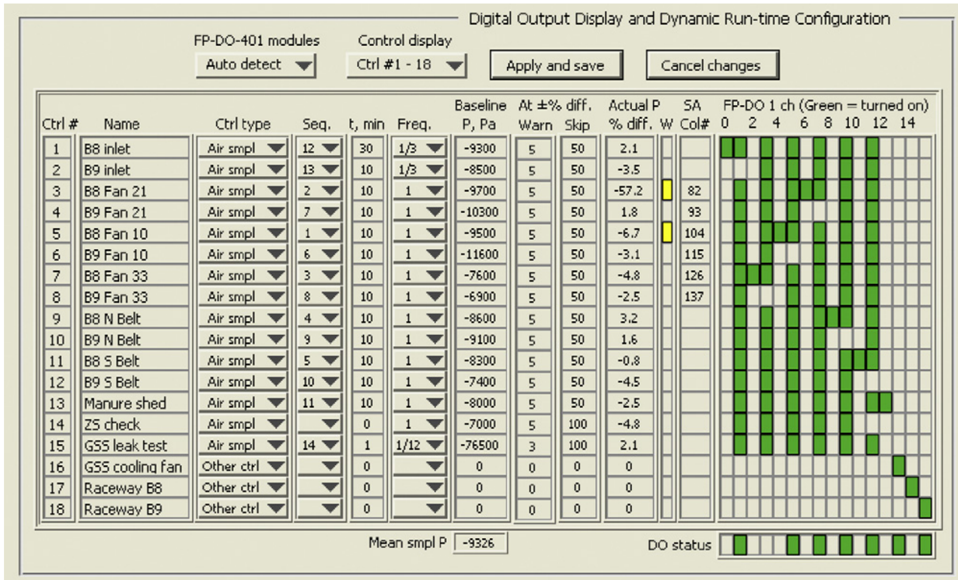


Fig. 5. AirDAC interface for Digital Output DDRC with an example configuration. Columns 1 “Ctrl#” to 6 “Freq.” are for air sampling and other control configuration. Columns 7 “Baseline” to 12 “SA” are for real-time sampling system monitoring and protection. The yellow-coloured cells in column “W” for Ctrl# 3 and 5 are visual warnings. The grid at the right is for digital output hardware channel configuration. The “Mean smpl P” and “DO status” display the real-time sampling pressure and hardware channel status, respectively.

sor analog output = offset ± S_i. Therefore, Eq. (7) is used to calculate the absolute value of X_i:

$$X_i = \left| \frac{(S_i - S_L) \cdot (R_H - R_L)}{S_H - S_L} + R_L \right| \tag{7}$$

The signal conversion setting for activity sensors is S_H = offset + 1, S_L = offset, R_H = 1, and R_L = 0.

3.3.4.3. Differential data acquisition signal. Processing of differential data acquisition signals are conducted by subtracting the reference voltage signals from the sensor signals using Eq. (8):

$$S_i = S_i - S_{D-n,i} \tag{8}$$

where $S_{D-n,i}$ = ith differential reference signal from the device at Global Channel number n.

3.4. Noval features in AirDAC

3.4.1. All-data Display and Dynamic Run-time Configuration

AirDAC provides a novel interface for users to conveniently configure real-time data processing, set data alarms and digital controls, and monitor all real-time data. This feature is realized with an All-data DDRC interface table, which contains 18 rows and a resizable number of columns (Fig. 4). AirDAC can acquire and process up to 500 data input channels depending on the scale of the project and computer speed. The first two columns are reserved for time and sampling location stamps and are non-configurable.

The 18 rows in the table are divided into four sections. The first section is a series of sequential integers automatically assigned by AirDAC at the top row (row 0) of the table. The numbers identify the measurement variables and correspond to the column numbers of the spreadsheet where data are saved. The second section (rows 1–10) is user-editable at run-time to configure data heading (row 1), data formatting (row 2), data conversion (rows 3–6), special functions for data processing (rows 7), data correction (rows 8 and 9), and Global Channel assignment (row 10). The third section (rows 11–14) is also user-editable at run-time for configuration of alarms and digital controls. The last section (rows 15–17) is for display of the signals acquired from instruments and sensors (row 15), data converted to engineering units (row 16), and data corrected and adjusted (row 17). Data in row 17 are ready to be averaged before saving into data files.

3.4.1.1. Special functions. Special Functions (row 7 of the All-data DDRC table) allow users to request AirDAC to perform special data processing for acquired signals from each channel. There are five Special Functions in AirDAC to satisfy the general needs in AAQ research.

1. “A”, to calculate absolute value of X_i for activity sensor using Eq. (7).
2. “D”, followed by the Global Channel number for subtracting S_i of differential reference signal (of the Global Channel) from S_i of the sensor signal using Eq. (8), e.g., “D23”.
3. “L”, for LSAS followed by a valid time in minutes, e.g., “L3”. The valid time is used by AirDAC in post-measurement data processing. This function instructs AirDAC to process the LSAS data separately from other measurement data.
4. “P”, to define the sampling pressure data column for real-time sampling system monitoring and protection (Fig. 5).
5. “W”, to calculate scalar wind direction (0–360°) when averaging Y_i using Eq. (6).

The Special Functions “A” and “W” can be combined with “D”, e.g., “WD18”, which requests AirDAC to subtract the S_i of Global Channel number 18 from the S_i of sensor signal and calculate the mean Y using scalar wind direction function (Eq. (6)). The “P” function can be combined with “L”, e.g., “PL7”.

3.4.1.2. Monitoring, visual alarm, and system control. Rows 11–14 in the table contain optional configuration for data monitoring and system control. The Min, Max, and Deadband (rows 11–13) define the range for Y_i and are used for Alarm & DO ctrl. (row 14), which defines what action to take if Y_i is within or out of the range. AirDAC checks the Y_i against the Min, Max, and Deadband in each column every second. For example, if Y_i is <Min or >Max, and if there is an action defined for alarm and control in row 14, a visual alarm by colouring the data column heading into yellow in the All-data DDRC table (Fig. 4), an alarm email to pre-defined recipients, and

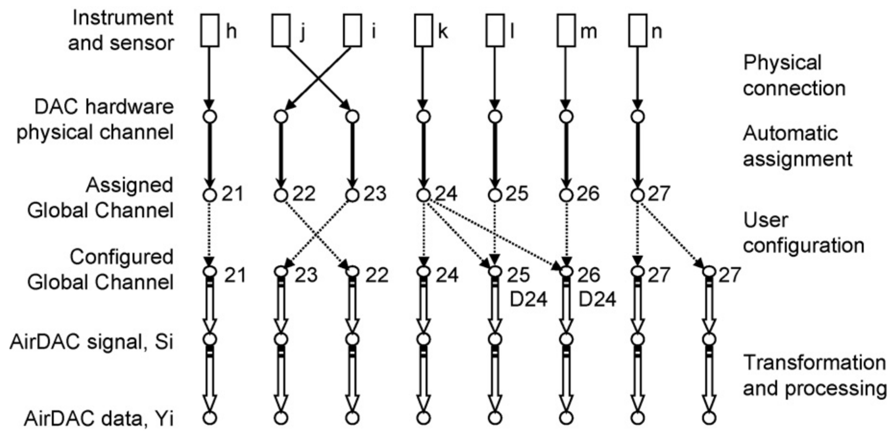


Fig. 6. Illustration of Global Channel configuration of AirDAC for data column correction (Global Channels #22 and 23), differential data acquisition (Global Channels #24–26, configured in rows 7 and 10 as shown in Fig. 4), and data duplication (Global Channel #27).

a DO control action are issued. Alarm and DO control are cancelled when Y_i becomes >(Min + Deadband) or <(Max − Deadband) if they have been trigged due to Y_i being out of range.

The syntax for Alarm & DO ctrl is: N{C,DO#}. Blank = no action. N: “1” = send email; “2” = send email and indicate sampling location number. C: “<” = check Min; “>” = check Max; “I” = within limits; “O” = out of limits. DO# = Ctrl # defined in tab “Digital Output DDRC” to turn on (Fig. 5). For example: “2{<,20}” = If Y_i < Min or Y_i > Max, send an automatic alarm email indicating sampling location #, and if Y_i < Min, turn on DO Ctrl #20.

3.4.1.3. Real-time all-data display. Rows 15–17 in the All-data DDRC table display all variables during data conversion, processing, and correction. These displays offer a convenient way to verify the data and troubleshoot the system. The S_i should have exactly the same values as the outputs of the data acquisition hardware. They can be compared with the values in the software provided by the hardware manufacturers, e.g., Measurement & Automation (MAX) by NI and InstaCal by MCC during troubleshooting. Any discrepancies are indications of a system problem. The mathematical relationships between rows 15 and 17 are defined in Eqs. (1), (4) and (7). Verifications during troubleshooting can be performed by using the parameters and special functions configured in the same column of the DDRC table.

3.4.2. Digital Output Display and Dynamic Run-time Configuration

AirDAC provides an interface for users to easily configure digital output control and check the current status of DO channels at run-time. This is realized with a Digital Output DDRC table, a user-editable interface and display (Fig. 5).

The sequence control number “Ctrl #” in Fig. 5 is automatically generated. The “Name” is user-entered for control identification. The DO configuration classifies all controls into two types, one for “Air smpl” and another for “Other ctrl”. The air sampling type is exclusive because only one air sampling control can be turned on by AirDAC at any given time, whereas multiple other controls can be turned on at the same time. The “Seq.” defines the automatic sampling sequence. The automatic sampling time is set at “Time, min”. The “Freq.” controls the automatic sampling frequency. When it is 1, the location is sampled every cycle. When it is $1/n$, AirDAC samples at that location once every n cycles. The grid at the right side of the table configures the FP-DO channel for each “Ctrl #”. Each cell in the grid can be turned on (green) or off (gray) during configuration by clicking on it. The bar below the table displays the run-time status of these channels.

The OSCS operates one or two FP-DO-401 modules (NI), each with 16 DO channels. Each channel can drive up to 2 A at 10–30 VDC and is suitable to control solenoids in a gas sampling system for multi-point sampling and other devices.

3.4.3. Real-time sampling system monitoring and protection

To ensure air tightness, assess maintenance requirements, and protect pump and solenoids of the sampling system, a real-time sampling system monitoring and protection feature was developed and interfaced into the Digital Output DDRC (Fig. 5). This task is realized by monitoring the real-time vacuum pressure at the sampling line and comparing it with the baseline pressure, which is pre-determined at non-leaking and new sampling filter conditions and configured in AirDAC. AirDAC issues a visual coloured warning or skips the sampling line if the percentage difference between the actual pressure and the baseline pressure at that line exceeds preselected levels for “Warn” and “Skip,” respectively. A negative % value in “Actual P” column indicates higher vacuum than the baseline P and is usually an indication of excessive dust accumulation in the sampling filter or sampling line blockage that needs maintenance or troubleshooting. A large positive value is usually a sign of leakage in the line. The SA (skip sampling line at data alarm) feature allows avoiding invalid sampling due to unfavourable sampling conditions. For example, sampling exhaust air at Barn 8 Fan #21 (Ctrl #3, Fig. 5), which is monitored with a vibration sensor, is skipped because the sensor indicates that the fan is not operating so the exhaust air is not available. The sensor signal and alarm are configured in column #82 in All-data DDRC table and is linked in Ctrl #3. For better QAQC in air sampling, the system can also be configured to perform automatic system leak tests by shutting off all the sampling solenoids and comparing the vacuum pressure with the baseline pressure at the same conditions (e.g., Ctrl #15, Fig. 5).

3.4.4. Global Channel

AirDAC introduces and uses the Global Channel for real-time data processing and QAQC. The Global Channel numbers are unique sequential numbers automatically assigned to each channel of the integrated devices (gas diluter and multi-gas monitor) and all physical input channels of the data acquisition hardware in use. The Global Channels offer AirDAC users the ability to select and assign in the All-data DDRC table for the following purposes (Fig. 6):

1. Arrange or correct data file columns. The flexibility of rearranging data columns allows users to keep the data file format consistent due to system modification or add-on projects. When the physical connection of instruments or sensors to the data acquisition hardware changes, the Global Channel number con-

figuration can be changed accordingly so that the data file format can remain unchanged. This is useful for reducing work load and error sources during subsequent data processing and, therefore, is beneficial for QAQC.
2. Perform differential data acquisition by using single-ended data acquisition hardware (Eq. (8)). This feature improves differential data acquisition when using hardware that does not have built-in differential feature (e.g., FieldPoint by NI). It also saves DAQ channel resources when one differential reference channel can be shared by several signals from the same sensor when using data acquisition hardware that has the differential option (e.g., USB AI 1600FS by MCC). For instance, it only needs five single-ended analog input channels, instead of eight in regular differential configuration, for differential data acquisition of an ultrasonic anemometer Model 81 000 (R. M. Young Co., Traverse City, Michigan) that has four analog outputs.
3. Duplicate data for a single measurement variable. For example, if a gas analyzer's raw signal (S) and calculated concentration (Y) both need to be saved in data files, the same Global Channel number can be assigned to two data columns and configured differently. To save averaged S_i, it simply needs to configure in the All-data DDRC table to make $Y_i = S_i$ in that column (S_L, R_L, and $B = 0$; S_H, R_H, and $A = 1$). Although data in these two columns are linearly correlated, they may provide some convenience for post-measurement data processing.

3.4.5. Automatic emails of alarms, data files, and active notifications

AirDAC employs LabVIEW's SMTP feature to send automatic emails of measurement alarms, daily data files, and 1-min data notification.

Alarm emails for each data column are user-configurable in row 14 shown in Fig. 4. When an alarm occurs, AirDAC sends an email indicating the measurement value, data column, alarm setting, and sampling location number (if requested). When the alarm is cancelled, AirDAC sends another email to notify the email recipients.

Data files of the previous day are sent after midnight to selected recipients. The Configuration file and Fieldnote file containing critical information about the system and human activity during measurement are also automatically sent to the email recipients after midnight if the files were updated during the previous day.

Active notification consisting of 1-min data of all variables being measured at a user-selected interval is an acknowledgment of system operation. No reception of this mail means system problems possibly associated with Internet downtime, computer shutdowns, software crashes, hard drive failures, power outages, or lightning strikes.

3.4.6. Integration of gas monitor and diluter

The Innova multi-gas monitor can measure concentrations of up to six different gases including water vapour and has been widely used in AAQ research in Europe and North America (e.g., Pratt et al., 2000; Heber et al., 2008; Moody et al., 2008). An Innova Controller sub-program that has a virtual Innova front panel as a user interface in the on-site computer was developed in AirDAC. The interface provides equivalent functions as the real Innova front panel and allows remote diagnosis and control of Innova. With this integration, AirDAC acquires, processes, and saves Innova data as all the other instruments and sensors.

The gas diluter controls and dilutes calibration gases for gas analyzer and sensor calibration. Integration of the Environics Model 4040 gas diluter is realized via data log files that are generated by the diluter. A Diluter Detector sub-program was developed in AirDAC to check the log files every second. When a newly updated log file is identified, the Diluter Detector reads and processes its contents. The calibration gas name, its actual concentration, and calibration time in the log file are acquired by AirDAC and saved into data files.

Integration of the diluter also increases the calibration accuracy when using the actual gas concentrations saved in log files. A comparison of the actual gas concentrations with its user-selected target gas concentrations using the Environics Model 4040 in 221 runs of four calibration gases demonstrated that the actual concentrations were consistently lower than the target concentrations, with a weighted mean of −0.41%.

3.4.7. Traceable configuration

Configurations of data acquisition hardware and real-time data processing are critical information for post-measurement data processing, analysis, and interpretation. These configurations are frequently adjusted or changed in long-term AAQ research measurements, due to various reasons, e.g., add-on projects, instrument measurement range changes, sampling location/time/frequency changes, data acquisition channel changes, etc. In AAQ studies without AirDAC, the changes are usually manually recorded, which are time-consuming and subject to omission and recording errors.

As an important QAQC measure, AirDAC includes a feature that automatically saves all configurations with a timestamp when they are applied. All hardware configurations are saved in a text file. All configurations related to data acquisition channel assignment and real-time processing, digital output control setting, and email setup are saved in a Microsoft Excel 2003 or Excel 2007 file. Individual parameters that are changed since last configuration are coloured in the Excel file for easy visual identification.

3.4.8. Post-measurement data processing

Post-measurement data processing is performed automatically after midnight with the previous day's data or with manual control at any time. It calculates the means of all measured variables with different time durations, i.e., 1, 2, 3, 4, 6, and 24 h. It also processes data from LSAS by separating gas concentrations and other variables according to their sampling locations and extracting valid data after excluding equilibrium time due to sampling line switching. The processed 1-min data and 2-h average LSAS data are plotted and presented graphically by using an Excel 2007 graph template.

This feature also includes searching and processing the data during gas analyzer calibrations. The acquired data during calibrations or precision checks are picked up from the 15-s raw data files and the responses of gas analyzers are calculated. The results are saved into data files to be used for studying the drifting of gas analyzers over time.

4. Application results

The Department of ABE, Purdue University started developing and implementing OSCS for a comprehensive AAQ research in 1997 (Heber et al., 2001). Continuous efforts to improve the system have been made since 2000 when several other comprehensive AAQ studies were conducted in laboratory, at experimental buildings, and commercial livestock and poultry farms. These efforts aimed at developing an OSCS that is based on state-of-the-art AAQ measurement requirements, readily configurable for different AAQ research projects, user-friendly, and strict QAQC.

As the result of the continuous development and application, 29 OSCS's have been developed and used in AAQ research at laboratories, experimental buildings, residential and agricultural areas, and commercial farms in 13 states in the U.S. (Table 2). The system is currently being used in the National Air Emission Monitoring

Table 2
List of applications of the OSCS in AAQ studies.

Year	Location, state	Study scale	Number of OSCS	Total time (OSCS-month)	Data points (million)
2000–2006	Indiana	Five lab tests on 42 manure additives	1	8	15
2004–2008	Indiana	Twelve rooms in a swine research building	1	12	69
2003–2006	Iowa, Missouri	Three ambient AAQ studies at residential and agricultural areas	2	10	8
2002–2003	Missouri	Two swine finishing barns	1	11	67
2001–2004	Indiana, Illinois, Iowa, Minnesota, North Carolina, Texas	Twelve barns at one broiler facility, two layer farm, and four pig farms	6	75	200
2004–2008	Ohio	Six barns at three layer farms	3	30	279
2007–2009	California, Indiana, Iowa, New York, North Carolina, Oklahoma, Washington, Wisconsin	Thirty-eight barns at five dairies, five pig farms, three layer farms, one layer manure shed, and one broiler facility	15	360	2400
Total	Thirteen states		29	506	3038

Study (NAEMS) to handle 2.4 billion data points, each containing four 15-s and one 60-s averages of one measurement variable, at 38 commercial livestock and poultry barns for a period of 2 years starting in 2007. By the beginning of 2010, the total application of the system will be 506 OSCS-month with 3.0 billion data points, which are more than all the data points collected in the world by other systems in AAQ studies.

5. Strengths, weaknesses, and future development needs

This OSCS was developed specifically to satisfy requirements of the growing number of comprehensive AAQ studies. Applicability, user-friendliness, and high level QAQC were the objectives throughout its development.

The system provides a configurable selection of general DAC hardware, measurement and control devices, air sampling methods, and data processing functions. It is readily applicable to most of the AAQ studies in laboratory and field conditions and is favourable for multi-institutional or international projects, where standardization of instrumentation and methods are required (Phillips et al., 1998).

The system also provides novel user interfaces that are comprehensive yet compact and easy to use. The interfaces offer convenience for future development. For instance, new data processing functions can be added in the Special Functions without changing the DDRC interface design.

The software structure provides maximum flexibility for different AAQ study projects. The separation of AirDAC Start and AirDAC Main programs leaves room for expansion of the OSCS to more commercial DAC hardware. The project-specific display program provides an option for individualized project monitoring feature. Research QAQC is significantly enhanced with features in this system such as integration of stand-alone instruments, dynamic real-time configuration, automatic and traceable documentation, real-time sampling system monitoring and protection, Global Channel, post-measurement data processing, and alarm and data delivery.

However, some useful features are still needed in the system. One of them is automatic protection of measurement devices, e.g., turning off the multi-gas monitor when harmful excess moisture is detected in the sampling air. More advanced pollutant concentration measurement instruments that have both analog output and serial communication options, e.g., chemiluminescence ammonia analyzer and TEOM, can be integrated into the system.

The system has limitations of using USB data acquisition devices, which must be connected directly to the computer USB ports. Data sampling speed cannot be maintained at 1 Hz when using external USB expansion hubs for extra USB DAQ devices. Even when not using USB hubs, the sampling speed can slow down if the number of USB devices exceeds six.

The system performance depends on the third party software of integrated devices. One example is that the response time of the integrated Environics gas diluter in AirDAC is affected by a bug in the Environics software, which causes the log files to be saved irregularly at unpredictable intervals. Another example is the limitation of the LabVIEW SMTP feature, which does not allow automatic email transfers via some of the Internet service providers.

More data processing functions, e.g., non-linear equations for data processing and real-time processing of the instrument calibration data, can be added to the system. More automatic instrument and equipment protection can also be developed. More commercial data acquisition hardware and stand-alone instruments will need to be integrated to make the system more adaptable to different research projects. Use of wireless sensors will be an important part of the future development.

Like all computers and electronics in agriculture, this OSCS needs continuous improvement. Its future development should focus on expanding its functional features and continuing enhancing QAQC. Its development should be based on emerging data acquisition requirements in AAQ research. New commercialized electronics and software products, such as computers, data acquisition hardware, and instruments and sensors will be the driving force for the future development of the system.

6. Conclusions

Development of computer technology and analytical instruments has enabled continuous and automated monitoring in AAQ research, which has dramatically increased its scope in the past half century. These changes have demanded advancement in methodology and technology for data acquisition, control, data processing, and communication in comprehensive AAQ research. Although AAQ studies differed from one to another, they had general requirements for sampling, measurement, and control. Regular and special instruments and sensors were used and multi-point sampling was applied. Reliable, powerful, and user-friendly OSCS that is easily applicable to different AAQ research can help not only reduce time and cost in measurement system development, operation, and data processing, but also increase data completeness and enhance project QAQC.

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