Air Quality Monitoring and Data Acquisition for Livestock and Poultry Environment Studies

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Abstract
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Keywords
Measurement, Control, Methodology, LabVIEW, Software, Instrumentation

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments

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Air Quality Monitoring and Data Acquisition for Livestock and Poultry Environment Studies

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Abstract. The development of analytical instruments and computer technologies in recent decades has facilitated significant changes in the methodologies used in scientific studies of agricultural air quality. A variety of instruments and sensors have been used for long-term and continuous measurements at commercial animal facilities and laboratories for determining baseline pollutant emissions and testing mitigation technologies. New measurement strategies were developed for real-time measurement and multi-location sampling. Optimization of this technology change necessitates an up-to-date system to acquire high-frequency data, control instruments and sampling locations, and monitor system operation. While various air quality research projects involve similar objectives and instrumentation to meet those objectives, they are usually conducted with monitoring plans that differ among sites and among projects. Special data acquisition and control (DAC) hardware and software have to be adapted for each monitoring plan. This paper summarizes various measurement and control devices used for comprehensive air quality studies of livestock and poultry environments. The paper further presents methods for real-time data transformation and processing. It introduces an air quality DAC system, which provided novel, flexible, and user-friendly features. The methodology and technology used in the new DAC system reduces system development and operational cost, increase reliability and work efficiency, and enhances data quality.

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Introduction

Agricultural air pollution has become an important environmental issue that has attracted more and more attention worldwide. Gases, particulate matter, and odor are the main concerns related to increasingly concentrated livestock and poultry production. Scientific research into agricultural air quality (AAQ) has seen dramatic changes in terms of monitoring scale, measurement duration, and the number of pollutants to be studied simultaneously. Monitoring time has increased from several days or weeks to more than two years to span across animal and bird growth cycles, manure accumulations, and seasonal variations of air pollution. Development of analytical instrumentation and computer technology has brought revolutionary changes to laboratory and field studies of air quality.

The technology of online sampling and measurement in AAQ research requires data acquisition and control (DAC) systems that satisfy high-frequency and multi-location sampling, multiple instrument measurement, and system monitoring. So far there are no commercial DAC systems developed specifically for comprehensive AAQ studies. The DAC systems must be custom developed for project-specific monitoring designs. While various air quality studies involve similar objectives and instrumentation, it usually requires that the DAC hardware be built and software be developed from scratch or modified substantially from old systems at the start of a project.

Individually developed DAC systems have several drawbacks. Firstly, the development of the measurement system, especially the software, is a very time consuming and expensive process. Realistically, most AAQ projects only have limited amount of time and money budgeted for developing such systems. Secondly, the resulting software only aims at satisfying the specific project. Therefore, it usually lacks user-friendly flexibility for hardware modification and DAC configuration. Thirdly, the work load for post-experimental data processing in AAQ research could be substantial if the DAC software does not provide effective and efficient quality assurance and quality control features.

A DAC system that satisfies all the general requirements of AAQ research but also meets the specific requirements of individual projects will significantly facilitate future research by reducing development and operation costs, increasing measurement accuracy, enhancing data reliability, and improving data quality.

The optimal DAC system should provide configurable features and user-friendly interfaces that give it the flexibility to be readily used in different projects. It also has to be based on state-of-the-art AAQ measurement technology. Although some detailed descriptions of individual measurement setups have been provided (van ‘t Klooster and Heitlage, 1992; Berckmans and Ni, 1993; Heber et al., 2001; Gates et al., 2005), the general requirement and methodology for designing DAC systems have not been systematically studied.
The objectives of this paper are to:
1. Compare the complexity of modern livestock/poultry AAQ studies with earlier studies.
2. Summarize the general requirements of data acquisition and control in modern AAQ research;
3. Introduce a new DAC system for AAQ studies.

**Development of Air Quality Research at Livestock and Poultry Farms**

Experimental studies of AAQ with air pollutant sampling and measurement on livestock and poultry farms started in the 1960s. Remarkable progress has been achieved during the past 40 years of research in this field.

**Expanded Research Objectives and Scales**

Early AAQ studies focused on identifying specific pollutant components (Day et al., 1965; Merkel et al., 1969), effect of ventilation on gas concentrations (Valentine, 1964), and effect of pollutants on worker and animal health (O’Donoghue, 1961; Charles and Payne, 1966; Doig and Willough, 1971). Information about levels of indoor pollutant concentrations was the primary technical objective of these studies.

Since the beginning of the 1980s, experimental AAQ studies in barns expanded from indoor air quality to include pollutant emissions and the subsequent health, environmental, and ecological impacts beyond the farm gate. The main objectives of these studies included: 1) determining pollutant concentrations and baseline emissions; 2) gaining insights into mechanisms of pollutant generation, release, emission, (spatial and temporal) distribution, and dispersion; and 3) testing mitigation technologies. The pollutants of interest were gases (including greenhouse gases), particulate matter, odor and odorous compounds, and pathogens.

The research scales became more diversified. Beside the survey types of studies and short term measurements (Meyer and Bundy, 1991), long-term measurement at multiple barns and national and international collaborative projects started (Sneath et al., 1997; Groot Koerkamp et al., 1998; Gates et al., 2005; Heber et al., 2006b; PAAQL, 2007).

**Increased Dataset Size**

The number of data obtained during AAQ research has increased exponentially in the past four decades. An air pollutant emission study in the 1960s could be based on 3 (Merkel et al., 1969) to 500 discrete gas concentration samples (Valentine, 1964).

Today, comprehensive monitoring projects are based on millions of continuously measured concentration, air flow, and other environmental data. The multi-state Aerial Pollutant Emissions from Confined Animal Buildings (APECAB) project (Heber et al., 2006b; Hoff et al., 2006), funded by USDA, resulted in 200 million data points, each consisting of a 1-min average of sixty, 1-s readings, after one year of continuous field measurement. The on-going National Air Emission Monitoring Study (NAEMS) will generate 2.4 billion data points during a 2-year field measurement campaign at 15 barn monitoring sites (PAAQL, 2007).

The number of measurement variables has also increased significantly since the 1960s. The study of Day et al. (1965) presented only pollutant concentrations. Valentine (1964) published results that had three variables, the ammonia concentration, temperature, and airflow rate. In the NAEMS barn monitoring effort, the largest on-going site is acquiring data continuously from more than 300 instruments and sensors every second. In addition to pollutant concentrations, sensors in the NAEMS are monitoring ventilation airflow rate, indoor air temperature and relative humidity, weather conditions, animal activity, and other variables.

**Expanded Measurement Methodology and Technology**

Advances in methodology and technology have changed the way that AAQ is studied. There have been a wide variety of sampling/measurement strategies undertaken for various AAQ projects. Sampling chambers for studying surface releases was also used for air sampling in animal building (Kroodsma et al., 1993). Micrometeorological methods were developed to determine gas emission at animal farms (Cassel et al., 2005). Open-path sampling/measurement using infrared or ultraviolet spectrum absorption is a relatively new technology for AAQ research (Shores et al., 2005). Centralized multiple-point sampling has become a popular method for gas and odor monitoring in animal buildings (Heber et al., 2006b).

An increasing number of instruments and sensors have either become available or have begun to be used for AAQ projects. For example, there have been 31 measurement instruments and sensors used for ammonia (NH₃) measurement at animal facilities (Ni and Heber, 2008). Since the introduction of the TEOM (Tapered Element Oscillating Microbalance) in AAQ, particulate matter measurement can be continuous and online (Heber et al., 2006a).

**Data Acquisition and Control for Agricultural Air Quality Research**

**Online and Offline Devices**

Devices including instruments, sensors, controllers, etc., used in AAQ research can be online or offline. Online devices can be connected to the central DAC computer while offline devices cannot.
Type 1 – Simple online measurement devices

Many sensors found in AAQ research are online devices. They include thermocouples, relative humidity sensors, certain gas monitors, activity sensors, and static pressure sensors. Their prices are usually in the low to middle range (< $5000).

Type 2 – Online-and-standalone measurement devices

Many advanced and more expensive instruments, e.g., gas analyzers and TEOMs, have built-in central processing units and data loggers. They usually have associated software that can be installed in the central DAC computer for instrument diagnosis, data downloads, and presentation via serial or Ethernet communication. Some of them also offer analog output to deliver measurement data to the DAC system. These instruments can operate alone and/or with the DAC computer. The use of the device software in the DAC computer is optional.

Type 3 – Offline-completely-standalone measurement devices

The most sophisticated and expensive instruments in AAQ studies, such as FTIR, GC-MS, dynamic olfactometers, and fan testers, are completely independent devices. They require a personal computer that has device-specific software installed to operate the instrument, but do not have an analog output. Their software offers a complete set of functions for data acquisition, processing, and presentation.

Type 4 – Offline measurement devices

There are also many devices used in AAQ studies that are offline direct reading devices, including gas tubes, regular rotameters, handheld anemometers, and psychrometers, that do not provide electronic output signals. Most of these devices are in the low price range (<$500) because of their simplicity in design.

Type 5 – Online control devices

Solenoids and relays in AAQ studies are online devices that can be controlled by the central DAC computers to select sampling air streams and to turn on/off heaters or motors.

Type 6 – Online-and-standalone device for control-and-measurement

Gas diluters are specialized devices that control the delivery of gases used in calibration of gas analyzers and at the same time monitor the type of gases and their delivery concentrations and flow rates.

Type 1 and Type 5 devices are readily connectable to the DAC system, as are Type 2 devices with analog outputs. Type 3, Type 6, and non-analog output Type 2 devices require custom software to be integrated into the centralized DAC system. Type 4 offline measurement devices cannot be used with DAC systems.

Signals and Communications of Online Measurement Devices

Online measurement devices offer different methods to connect to or to communicate with the DAC computer. Signal output to the DAC system is one-way data traffic to provide device response information to the DAC computer. Communication with the PC is two-way data and control signal traffic between the device and the PC, which can send commands to, and receive feedback from, the measurement device. Table 1 lists some of the most commonly used online devices and their signals and communications.

Analog and digital signals

Most of the online measurement devices provide analog or digital (binary) on/off signals that can be readily acquired by analog input or digital input DAQ hardware, respectively.

Pulse signals

The outputs of some measurement devices, usually corresponding to rotational motions such as magnetic proximity sensors used to measure fan rotational speed (denoted as rpm sensors) and certain wind speed sensors, are high-frequency digital signals or pulses. Counter DAQ hardware and software is typically used to acquire these signals and convert them into frequency data.

Serial port communication

Devices that provide only serial port communications with the DAC PC do not require DAQ hardware, but can not be readily integrated into the centralized DAC system.

Location-Shared Analyzers and Sensors and Online Device Controls

Location-shared analyzers and sensors (LSAS) are devices used to measure air samples from multiple locations, from which sample air is transported via sampling tubing with an automatic control system to the measurement LSAS. The advantages of LSAS are that errors introduced by different instruments/sensors are minimized and cost of expensive instruments is reduced. The DAC system controls the sampling location, time, sequence, and frequency of LSAS measurement. The location numbers and measurement data corresponding to those locations are recorded in the computer by the DAC system.
Other devices that are most often controlled online by the DAC system include air sampling line heating, sampling pumps, and cooling fans. These controls, including the sampling locations, are usually on/off controls using digital output DAC hardware.

Table 1. Most commonly used online instruments and sensors in AAQ research

<table>
<thead>
<tr>
<th>Measurement purpose</th>
<th>Instrument or sensors</th>
<th>Signal or interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas concentration</td>
<td>Gas analyzer, Multi-gas analyzer</td>
<td>Analog, serial</td>
</tr>
<tr>
<td>PM concentration</td>
<td>Real-time PM monitors</td>
<td>Analog, serial</td>
</tr>
<tr>
<td>Temperature</td>
<td>Thermocouple, temperature sensor</td>
<td>Analog</td>
</tr>
<tr>
<td>Air humidity</td>
<td>Relative humidity sensor</td>
<td>Analog</td>
</tr>
<tr>
<td>Fan on/off monitoring</td>
<td>Vibration sensor, current switch, relay contact</td>
<td>Digital</td>
</tr>
<tr>
<td>Fan control signal</td>
<td>Current sensor</td>
<td>Analog</td>
</tr>
<tr>
<td>Fan rotation speed</td>
<td>RPM sensor</td>
<td>Pulse</td>
</tr>
<tr>
<td>Ventilation air speed</td>
<td>Anemometer</td>
<td>Analog, pulse</td>
</tr>
<tr>
<td>Weather condition</td>
<td>Solar radiation</td>
<td>Analog</td>
</tr>
<tr>
<td>Wind direction</td>
<td>Analog</td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>Analog, pulse</td>
<td></td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>Analog</td>
<td></td>
</tr>
<tr>
<td>Ventilation efficiency</td>
<td>Pressure sensor</td>
<td>Analog</td>
</tr>
<tr>
<td>Animal/worker activity</td>
<td>Activity sensors</td>
<td>Analog</td>
</tr>
<tr>
<td>Calibration gases</td>
<td>Gas diluter</td>
<td>Serial</td>
</tr>
</tbody>
</table>

Monitoring of Experimental System

Comprehensive AAQ studies are usually designed for long-term monitoring, in which the measurement systems are unattended during the majority of the measurement time. Advanced DAC should include features to monitor the experimental system and issue alarms upon detection of any abnormalities.

Most commonly required system monitoring takes account of the environment where the instruments are housed. Temperature, relative humidity, and pressure of that environment are most commonly monitored. Evaluating all measurement data in real-time and ensuring they are operating within acceptable ranges is an effective way of system monitoring, because a failed sensor or instrument usually outputs data that are outside its normal range.

Real-time Data File Integration

Measurement data from some online-standalone devices can be saved in built-in data loggers and downloaded to the PC using device specific software via serial communications, or be logged into data files real-time by the PC. These data are stored in manufacturer-defined formats, data logging intervals, and timestamps provided by the instrument internal clock. The format and data logging intervals are usually different from the central DAC system in AAQ studies. The timestamps from the devices and from the PC cannot be guaranteed to match due to clock deviation.

When the data from these devices are only part of the measurements in the AAQ project, the data logged by the devices have to be matched with the data from other instruments and sensors. This can be done manually, or with the help of custom-developed computer programs. Differences in timestamps are an error source, and must be carefully monitored.

Experience shows that when data from all devices are integrated in real-time into a single data file, errors are reduced, as are cost and time during post-measurement data processing. Therefore, all acquired data should be orderly arranged in integrated data files whenever possible. Special sub-programs may need to be developed for specific devices in order to facilitate this integration.

A Data Acquisition and Control System for Agricultural Air Quality Studies

To meet the requirements of different AAQ research projects, Purdue University developed a new DAC system for laboratory and field experiments. This system consists of commercial data acquisition hardware and custom-developed software. In addition, it uses commercial software (pcAnywhere) for remote access and control via internet connection (Figure 1).

This new DAC system aims to provide: 1) flexibility and user-friendly configuration for various AAQ projects and their add-on projects, 2) capacity for acquiring large number of data from up to 500 channels at high sampling rate (1 Hz), 3) ease of dynamic real-time analog and digital configuration, 4) convenience of table and graphical displays, 5) integration of stand-alone instruments into the system, and 6) improvement of quality assurance and quality control. It has been used in seven laboratory and 30 field studies in 13 states in the U.S. since 2000.
Hardware and Software

The system uses products from two major data acquisition hardware manufacturers, National Instruments (NI, Austin, TX), and Measurement Computing Corporation (MCC, Norton, MA). FieldPoint modules from NI provide high quality data acquisition. One or more banks of FieldPoint modules are connected to the Central DAC PC via Ethernet cables. Each bank can contain up to nine selectable modules for analog input, thermocouple, and digital output. USB devices include analog I/O, digital I/O, and counter modules from MCC. They are relatively low cost and flexible for configuration. These products can satisfy the general requirements of AAQ studies discussed above.

The DAC software, AirDAC, is written in LabVIEW (NI), which is a graphical development environment with built-in functionality for data acquisition, instrument control, measurement analysis, and data presentation. LabVIEW provides the flexibility of a powerful programming language without the complexity of traditional development environments (Elliotta et al., 2007), and has been used in AAQ studies (Boriack et al., 2004; Wheeler et al., 2007). AirDAC provides features that allow users to select and configure NI and MCC hardware, digital output controls, and system monitoring, and to perform dynamic run-time configuration for data transformation and processing. AirDAC also includes two sub-programs that work with two online standalone devices, the Innova multi-gas monitor and the Environics gas diluter (Figure 1).

Data Transformation, Correction, and Averaging

The algorithm of data transformation and processing in AirDAC was based on the characteristics of the measurement devices in AAQ studies. Data transformation in AirDAC is for unit conversion and is done in real-time.

General Data Transformation

Analog signal outputs from commercial analyzers and sensors, either as a voltage or as current, are normally linear and have fixed or user-selectable signal ranges (e.g., from 0 to 10 VDC or from 0.004 to 0.020 A). Analyzers and sensors also have 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 data transformation equation that is based on signal range and measurement range to convert analog, digital, and pulse signals from all measurement devices.

Data Correction and Averaging

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 calibration coefficients of the analyzer), AirDAC provides
data correction options for all data channels with a linear equation. AirDAC averages the transformed 1-s data readings to 15-s and 1-min means, and saves them in two separate data files.

**Special Transformation and Processing**

**Activity Sensor Signals**

Signals from activity sensors require special transformation because they have an offset voltage and the sensor analog output = offset ± signal. A special function (SF) flag was built into AirDAC. When SF = 1 is selected for a specific sensor, AirDAC calculates the absolute value of the transformed sensor data before the data are averaged.

**Digital Sensor Signals**

For sensors with digital output signals, AirDAC performs a pre-conversion by multiplying the binary signal by 100, so that the signal represents either 0% or 100% time for the on/off status of the device that the sensor monitors.

**Wind Direction Data**

Wind direction is a circular function with values between 1 and 360 degrees after data transformation. The wind direction discontinuity at the beginning/end of the scale requires special data processing to compute a valid mean value. A single-pass procedure was recommended in Webmet.com (2006). The method assumes that the difference between successive wind direction samples is less than 180 degrees; to ensure such, a sampling rate of once per second or greater should be used to compute the scalar mean wind direction.

A SF flag (the number “360”) is designed for each DAQ channel in AirDAC for a special wind direction function. At this flag, AirDAC processes the wind direction data on \( n \) samples (\( n = 15 \) or 60) using the Webmet.com scalar equations to average the samples before they are saved in data files.

**All Data Display and Dynamic Run-time Configuration**

AirDAC provides a novel interface for users to easily check all data and configure data transformation and processing during run-time. This was realized with a data Display and Dynamic Run-time Configuration (DDRC) table, which is resizable from 2 to 500 data columns depending on the measurement devices and DAQ hardware in use. The table includes 14 editable rows of DDRC for data transformation, correction, DAQ channel arrangement, system monitoring, and linkage to digital controls. It also includes three non-editable rows for displaying the signals, converted values, and corrected data for all the measurement devices.

**Digital Output Dynamic Run-time Configuration**

AirDAC controls one or two FP-DO-401 modules (NI), each with 16 digital output (DO) channels. Each FP-DO-401 channel can drive up to 2 A at 10-30 VDC and is suitable for controlling solenoid valves in a gas sampling system for multi-location sampling (Heber et al., 2006b), and other devices.

AirDAC provides a user-interface for easily configuring DO control and checking the current status of DO channels in real time. This was accomplished with a digital output Dynamic Run-time Configuration (DRC) table, which allows users to easily set up multiple-point air sampling including sampling location name, time, sequence, and frequency for each location. The frequency controls automatic sampling. For example, a frequency of 1 means the location is sampled once per cycle. When it is set at \( 1/n \), the sampling at that location will be conducted once every \( n \) cycles.

The DO configuration classifies all controls into two groups, one for “Air Sampling” and another for “Other Controls”. Air Sampling is exclusive. Only one air sampling DO channel can be turned on by AirDAC at any given time. Multiple Other Control channels can be turned on at the same time.

**Emails for Alarm, Data, and Notification**

For system monitoring and data delivery, AirDAC uses LabVIEW’s SMTP feature to send automatic emails for measurement alarms, daily data files and 1-min data notifications. Alarm emails for each measurement variable is user-defined in the data DDRC table. 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 same recipients.

Data files of the previous day are emailed at midnight to designated recipients. Active notification consists of an email containing 1-min of data at user-selected intervals. This feature is to notify the operator that the system is running normally when it is unattended. No email received is an alert of possible system problems, including lightning strikes, internet failures, PC problems, software crashes, power failures, etc.

**Integration of Standalone Devices**

The DAC system integrates two online standalone devices. They are the Innova Photoacoustic Gas-Monitor (California Analytical Instruments, Orange, CA) and the Environics gas diluter (Environics Inc.,
The Innova gas monitor can measure concentrations of up to five different gases plus water vapor. The diluter is employed for calibration of gas analyzers.

An Innova Controller subprogram was developed and integrated into AirDAC. The Controller includes a virtual instrument front panel as the interface between the DAC PC and the Innova. It acquires data into AirDAC to be processed and saved in the same file as the data from all other instruments and sensors. This interface also allows remote diagnostic and control of the Innova.

Integration of the gas diluter is made possible via the data log file that is generated by the diluter. A Gas Diluter Detector sub-program was developed in AirDAC to detect the recently saved log files every second. If a log file saved within 20 s is detected, the Detector reads the contents of the file, interprets the log information, and provides selected data to AirDAC. The name of the calibration gas, its actual concentration, and calibration time are saved into AirDAC data files.

Traceable DAC Configuration

Configurations of DAC hardware, data transformation, and data processing are critical information for post-measurement data processing, analysis, and interpretation. During long-term measurements, these configurations are often adjusted or changed for various reasons, e.g., add-on projects, instrument measurement range changes, sampling location/time/frequency changes, data acquisition channel changes, etc. These changes are usually manually recorded, which is time-consuming, and can be a source of errors and omissions.

As an important quality assurance and quality control measure, AirDAC includes functions that automatically save all new configurations with a timestamp when they are applied. All hardware configuration histories are saved in a text file. All configuration histories related to DAC channel assignment, data transformation and processing, digital output control settings, and email setups are saved in an Excel 2003 or Excel 2007 file. Individual parameters that are changed since the last configuration are colored in the Excel file for easy visual identification.

Summary

Development of analytical instruments and computer technology has enabled continuous and automated monitoring in AAQ studies, which have dramatically increased their sizes and scopes, demanding advancement in methodology and technology for efficient data acquisition and control.

Online measurement and control devices are preferred in AAQ studies for continuous measurement and automation. Most online measurement devices used in comprehensive AAQ studies provide either analog, digital, or pulse signals. They can be readily connected to the central DAC system. Other devices that are standalone need custom DAC programs for integration. Real-time integration of different devices in the central DAC system reduces errors and saves time in post-measurement data processing, and should be done whenever possible.

System control requirements in comprehensive AAQ studies include regulating air sampling time, location, sequence, and frequency for the location-shared analyzers and sensors. It also includes control of heating and cooling systems, and pumps required for air sampling. All these controls can be realized with on/off DO control. In unattended measurement systems, continuous monitoring of operational status is also important for the DAC system.

A DAC system that has been used in more than 30 laboratory and field studies in 13 states was introduced. It consists of commercial DAC hardware and custom-software AirDAC. It also uses commercial software (pcAnywhere) for remote access and control. The system provides configurable and user-friendly interfaces with dynamic real-time configuration, system monitoring, and integration of standalone devices. This system in AAQ studies reduces the time for measurement system development, increases data quality, and saves time in data processing.

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