An Electronic Nose Network System for Online Monitoring of Livestock Farm Odors
Leilei Pan and Simon X. Yang

Abstract—An electronic nose (e-nose)-based network system is developed for monitoring odors in and around livestock farms remotely. This network is built from compact e-noses that are tailored to measure odor compounds and environmental conditions such as temperature, wind speed, and humidity. The e-noses are placed at various applicable locations in and around the farm, and the collected odor data are transmitted via wireless network to a computer server, where the data processing algorithms process and analyze the data. The developed e-nose network system enables more effective odor management capabilities for more efficient operation of odor control practice by providing consistent, comprehensive, real-time data about the environment and odor profile in and around the livestock farms. Experimental and simulation results demonstrate the effectiveness of the developed system.

Index Terms—Electronic nose (e-nose), odor dispersion, odor monitoring, wireless sensor network.

I. INTRODUCTION

Odor emissions from livestock operations have caused significant public concerns about the environment and human health. Odor control technologies are greatly impeded by the lack of science-based approaches to assess the effects of odor. With the current state of technology, the most commonly used methods to measure odor from livestock facilities is human sniffing methods. Odor measurement technologies such as olfactometry and scentometer use trained odor panelists to smell air samples to determine the strength of an odor [1]. Both olfactometry and scentometer methods are expensive to use and are susceptible to the assessor’s personal bias. Therefore, unbiased automatic odor evaluation technologies are desirable. An electronic nose (e-nose) is such a reliable alternative for objectively measuring livestock farm odors.

Now, e-noses have been developed for monitoring agricultural environment. In our previous study, an e-nose consisting of a sensor array and an intelligent analysis system was developed. Experimental results proved its capability of producing objective and consistent odor measurement [2].

However, an e-nose is not enough to provide a comprehensive odor profile in and around the livestock facility. The impact area of odorous gas emissions is difficult to determine because it continuously changes with wind speed and direction. In addition, a modern livestock facility is usually a point odor source but rather an array of points (exhaust fans, lines (side curtain opening), and areas (outdoor storage surfaces). An e-nose can only measure the odor at one location; it cannot provide an overall odor profile around livestock facilities that is necessary for a comprehensive and efficient odor management strategy.

II. DEVELOPED WIRELESS ELECTRONIC NOSE NETWORK SYSTEM

In this study, an e-nose network system is developed for remotely monitoring and analyzing livestock farm odors in real time. The development of the proposed wireless e-nose network system includes following parts: the design of several simplified e-noses for measuring odor components and environmental conditions, the network architecture design, the design of a software suite to process and analyze the odor data, the development of data processing and analysis algorithms, and the integration of the whole network system.

The architecture of the developed wireless e-nose network system is illustrated in Fig. 1. Essentially, the wireless e-nose network is a simple STAR network. STAR is a common network topology, with all the sensor nodes communicating with a central control station (also called sink or gateway). The wireless e-nose network system consists of various hardware components. In this section, the architecture of the wireless e-nose network system is presented.
network and the development of essential hardware components are presented.

A. Development of the Electronic Noses

To be utilized in the wireless network, the e-noses should be compact in size, energy efficient, and of low cost. The design toward the final e-nose for the wireless sensor network includes several steps, such as the selection of sensors to measure odorous compounds most prevalent in livestock odor, the incorporation of these sensors into a sensory array, the design of a chamber to regulate gases toward the sensors, and the acquisition of the sensor array data for wireless transfer.

1) Sensor Selection and Sensor Array: Each e-nose in the network has a sensor array with four gas sensors to measure odor components in ambient air, and two sensors to measure the environmental conditions, i.e., a humidity sensor and a temperature sensor. The gas sensors are selected based on previous extensive investigation and experiments, as well as various sensors available for odor compound measurement. These four sensors can measure most of the major gas compounds in livestock farm odors. A section of this sensor list is shown in Table I. The selected sensors are fixed in an array. A developed sensor array is shown in Fig. 2.

2) Design of the Chamber: A chamber is designed to accommodate the sensor array and regulate the flow of odorous air. The sensor array is placed within this chamber, and the odorous air is directed toward the array. Since the sensors have specific requirements on the airflow rate for proper operation, a pump is used to control the airflow speed.

The chamber also contains a simple diffuser to disperse the incoming odorous air or filtered clean air onto the sensor array. The sensor array faces directly into the coming air so that the surface area of the array that is exposed to the odorous air is maximized. This ensures best measuring results and minimizes the possibility of attaining improper readings. The chamber also has an input valve that is switched between odorous and carbon filtered air ports, so that the filtered odorous air can refresh the chamber and sensor when necessary.

3) Integration of the Electronic Nose: The analog sensor signals collected by the e-nose are converted to 12-bit digital signals by a data acquisition board (MDA300) right at the e-nose side. The multifunction data acquisition board MDA300 can convert up to 11 channels of analog inputs. The input analog signals range from 0 to 2.5 V, and the output digital signals range from 0 to 4095. The digital signals are delivered by a 2.4-GHz mote (MPR2400) to a gateway. Gas sensors and the air pump are powered by a 12-V dc power supply. A developed e-nose system is shown in Fig. 3. These small battery-powered e-noses are placed in locations of interest around livestock facilities to collect odor data. The e-nose network prototype consists of three e-noses at this time, which can be easily expanded to accommodate more e-noses when necessary. Usually, if an e-nose fails, other e-noses that cover the area can also provide the missing information. For instance, if e-noses A, B, and C all provide coverage of area G, when nose A fails, noses B and C still provide information on area G. Therefore, the more e-noses in a certain area, the more robust the wireless network system is to the sensor failure. However, larger density of e-noses costs more, and larger redundant information could make wireless transmission slow.

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Compounds</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>ethanol, ammonia, propionic acid, 2-butanol, H2S, trimethylamine, acetic acid, benzyl alcohol</td>
<td>tin dioxide</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>Amine Compounds</td>
<td>tungsten oxide</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

**Fig. 1. Architecture of the developed wireless e-nose network.**

**Table I**

Sensors Used in the Development of the E-Nose

**Fig. 2. Developed sensor array.**

**Fig. 3. Developed e-nose consists of the sensor array inside a chamber, a data acquisition board, a mote processor, and a power supply.**
B. Electronic Nose Network

The odor data collected by the e-noses located in and around the farm are delivered by a 2.4-GHz wireless LAN to the gateway. The gateway gathers the sensor signals and inputs them into the control center via Ethernet. The block diagram of the wireless network is shown in Fig. 4.

For the purposes of wireless transmission of sensor signals, in this research, the MicaZ wireless network platform from Crossbow (Crossbow Technology, Inc., USA) is adopted. This wireless network platform has advantages of the small physical size, low cost, and low power consumption, making it ideal for this odor monitoring application.

The small, low-power radio and processor board MPR2400 includes a processor, radio, and battery. Power can be provided by any 3-V power source, typically two AA batteries. The radio on the MPR module consists of a basic 2.4-GHz industrial, scientific and medical (ISM) band transceiver that is compliant to IEEE 802.15.4/ZigBee protocol, an antenna, and collection of discrete components to configure the physical layer characteristics, such as signal strength and sensitivity. The gateway MIB600 provides Ethernet connectivity for communication, and allows remote access to the e-nose network data via Transmission Control Protocol (TCP)/IP. The wireless communication ability not only enables sensor data and status information to be communicated across the network, but also enables remote control of network nodes.

C. Data Processing and Analysis

Odor data collected by the e-noses need to be processed and analyzed to identify rules and patterns in the data. Several signal processing algorithms and pattern analysis techniques are used to analyze and process sensor data.

1) Noise Reduction: Sensor signals generated by the e-nose usually are contaminated by white noise. Noise reduction is the process of removing noise from a signal. There are many noise reduction methods to remove or reduce noise from sensor signals, such as commonly used fast Fourier transforms, Kalman filters, and moving average filters. In this research, moving average technology is adopted to reduce noises in the sensor signals as it is fast in computing and easy to use in comparison to other existing technologies. An exponentially weighted moving average filter is used to minimize the noise [18]. The filter is given as

$$ \bar{x}_k = \frac{n}{n+1} \bar{x}_{k-1} + \left( 1 - \frac{n}{n+1} \right) x_k $$

where \( n \) is number of data points in the filter, \( k \) is the \( k \)th data point, and \( \bar{x}_k \) is a simple moving average filter given by

$$ \bar{x}_k = \frac{1}{n} \sum_{i=k-n+1}^{k} x_i $$

This method applies weighting factors to the data points in the way that the weights for earlier data decrease exponentially, thus giving much more importance to recent observations while still not discarding previous observations entirely.

2) Compensation for Signal Drift: Sensor signals are usually subjected to temporal variation, typically referred to as "long-term drift," due to temperature and humidity changes in the environment. This drift may seriously influence calibration; therefore, drift compensation approaches are used to reduce the drift. These approaches include mathematical methods based on curve fitting of the temporal variation of the sensor signals, wavelet analysis, or statistic methods such as principal components analysis. In this study, a simple data preprocessing algorithm is used to compensate the signal drift. This method compensates the variation of the conductance of the sensors that are caused by environmental changes, and therefore reduces the variation of the output electrical signals of the sensors. The general expression of the compensation approach is given as

$$ r_{ij} = \frac{G_{ij} - G^0_{ij}}{G^0_{ij}} $$

where \( G^0_{ij} \) is the conductance of the sensor \( i \) in clean air (i.e., baseline signal) and \( G_{ij} \) is the conductance of the sensor \( i \) in the presence of odor \( j \) [8].

3) Modeling of Odor Dispersion: Accurately measuring odors in and around the livestock farms has been an elusive goal of researchers and livestock producers. Air dispersion models have been applied to evaluate odor impacts around the livestock facilities and determine the setback distance between the livestock facilities and local residents [6]. Various types of dispersion models have been developed to represent different types of emission release scenarios. Commonly used dispersion models for livestock farm odor dispersion include numerical advection–diffusion models, Gaussian models, and Lagrangian particle trajectory theory. Gaussian dispersion models are used for steady-state meteorology conditions, and therefore are not suitable for modeling dynamic odor dispersion on livestock farms [15]. Numerical approaches and Lagrangian particle trajectory approaches are complicated, and require the high computational and memory capacity, and therefore are not ideal for online odor analysis [5], [16]. As livestock farms have special odor emissions, farmsteads, and odor management systems, an ad hoc livestock farm odor dispersion model can greatly improve the efficiency and accuracy of odor dispersion prediction.

A neural network model is proposed for modeling dynamic odor dispersion around livestock farms. The neural dynamics of each neuron is characterized by a shunting equation of an additive equation derived from Hodgkin and Huxley’s membrane equation [7]. A 2-D dynamic odor dispersion model is proposed as

$$ \frac{dC(X_i,t)}{dt} = -AC(X_i,t) + (B - C(X_i,t)) $$

$$ (\left[ I(X_i,t) \right]^+ + \sum_{j=1}^{N} w_{ij} [C(X_j,t)]^+ ) $$

$$ - (D + C(X_i,t)) [I(X_i,t)]^- $$

where \( X_i = (x, y) \) is the location of the \( i \)th neuron, \( i = 1, 2, \ldots, N \), \( N \) is the total number of neighboring neurons of the \( i \)th neuron, \( x \) is the...
downwind distance of the $i$th neuron to the odor source, while $y$ is the crosswind distance of the $i$th neuron to the odor source, $C(X_i, t)$ is the odor concentration at the $i$th neuron, and $[I(X_i, t)]^+$ and $[I(X_i, t)]^-$ are excitatory and inhibitory inputs, respectively, where $[e]^+$ and $[e]^-$ are linear-above-threshold functions defined as

$$
\begin{cases}
[e]^+ = \max \{e, 0\} \\
[e]^- = \max \{-e, 0\}.
\end{cases}
$$

Parameters $A$, $B$, and $D$ represent the passive decay rate, the upper and lower bounds of the neural activity, respectively. Parameters $B$ and $D$ are constants, and $A$ can be a function of wind speed, i.e.,

$$A = qW(t)$$

where $q$ is a positive constant and $W(t)$ represents the wind speed at time $t$. Therefore, parameter $A$ represents the transportation effect of airflow; the higher the airflow speed, the faster the odorous compounds being dispersed.

The variable $I(X_i, t)$ is external input to the $i$th neuron defined as

$$I(X_i, t) = \begin{cases}
S(t), & \text{if there is an odor source at position } X_i \\
-R(t), & \text{if there is an odor reduction means at position } X_i \\
0, & \text{if there is no odor source or reduction means at position } X_i
\end{cases}$$

where $S(t)$ and $R(t)$ are positive functions of time. The odor reduction means include odor control practice operated by livestock producers, dry deposition to the earth surface, and wet deposition by precipitation (rain, fog, snow, etc.).

In (4), item $\sum_{j=1}^N w_{ij}[C(X_j, t)]^+$ represents the interaction among the neighbor neurons, where $N$ is the total number of neighboring neurons of the $i$th neuron and $w_{ij}$ is the connection weight from $j$th neuron to the $i$th neuron, which is a function of distance defined as

$$w_{ij} = \begin{cases}
0, & \text{if } d_{ij} > r_0 \\
u \frac{d_{ij}}{d_{ij}}, & \text{if } d_{ij} \leq r_0
\end{cases}$$

where $r_0$ is a positive constant and $d_{ij} = |X_i - X_j|$ represents the Euclidean distance between positions $X_i$ and $X_j$ in the state space. Therefore, the neuron has only local lateral connections in a small region $(0, r_0)$. Function $u$ is a function of wind direction, which is defined as

$$u(\theta) = -E \cos \left( \frac{\theta}{2} \right)$$

where $\theta$ is the angle between the wind direction and the position of the neighbor neuron. When $0 \leq \theta \leq 90$, the neighbor position $X_j$ is downwind of $X_i$, the position being inspected; therefore, odor emissions are transported from position $X_j$ to $X_i$, which causes a depletion of odor concentration/intensity at position $X_i$; when $90 < \theta \leq 180$, the neighbor position $X_j$ is upwind of $X_i$; therefore, odor emissions are transported from position $X_i$ to $X_j$, which results in a replenishment of odor concentration/intensity at $X_j$; when $\theta = 180$ or $\theta = 0$, the position $X_j$ is right on the centerline of the wind direction; therefore, the odor concentration/intensity at $X_j$ yields a maximum replenishment/depletion effect.

The emission rate from the odor source, the environment conditions (such as wind direction and speed), and farming activities (such as spreading manure, applying odor reduction means) may vary with time. The activity landscape of the neural network dynamically changes due to the varying external inputs and the internal neural connections, and therefore dynamically represents the changes of odor dispersion.

An example of calculated odor dispersion from a point source is shown in Fig. 5. The 2-D odor dispersion at receptor’s height is shown in Fig. 5(a), downwind along plume centerline in Fig. 5(b), and along crosswind direction in Fig. 5(c).

Previous research on odor dispersion indicated that the location of the e-noses would influence the measurement results and the odor dispersion model. The odor dispersion plume is usually affected by the landscape around the farm such as vegetation and buildings. For example, high crops in the field serve as windbreaks, which would greatly reduce the odor dispersion [15]. A building could cause a downwash effect, e.g., airflow forms a “cavity” with recirculating flow downwind of the building, which would greatly change the odor dispersion close to that building [17]. Therefore, it is important to make sure that the odor information around these locations is available by deploying sensor nodes to these locations.

### D. Software Integration

In order to utilize the previously mentioned hardware, certain software packages are needed. The MDA300, the MICAz, and the MIB600 all run on TinyOS programming language. An application provided with the hardware called MoteWorks is sufficient to set up a wireless network for data transfer. This involved placing the gateway (MIB600) in the same subnet as the client station and using a simple hub to successfully place the device onto the network. Then, MoteWorks autoconfigures and acquires the IP address of the network. Once the gateway device is active, the mote is programmed to interface with the e-noses. Then, the wireless network system can be integrated and synchronized. An application software called MoteView from Crossbow (Crossbow Technology, Inc., USA) can automatically detect the e-nose and the gateway, and receive data from the e-nose through the wireless network. The topology of the wireless network interface is shown in Fig. 6.

The odor data collected by the e-nose network need to be processed and analyzed for the purpose of supporting odor control decisions. Hence, software suite is designed for real-time data capture, display, and analysis. The software is running on a central analysis station, and includes four main components: 1) a data acquisition system to...
acquire the sensor signals that are transferred to the computer via the wireless network; 2) a database that stores the odor data for future applications; 3) an odor analysis system that identifies risk factors of odor and calculates odor concentration and odor dispersion plume; and 4) a user interface tire that interacts with users and displays odor data and reports analysis results.

1) Data Acquisition System: After analog sensor signals are converted into digital signals, the digital signals are sent wirelessly through the wireless network to the gateway, which receives and collect the digital signals. Then, the data acquisition system in the computer will interface with the gateway and acquire the digital signals into the database.

2) Database: Database plays an important role as a data storage, management, and exchange center for various applications. In this system, data structures (data records and files) are optimized to deal with large amounts of data. A data storage system based on Microsoft SQL Server 2005 database server is developed for storing sensor signals and odor information. The stored odor data in the database can be retrieved, managed, and processed through user interface.

3) User Interface Tire: Users interact with the control station directly through a series of user interfaces. These interfaces are within the user interface layer. The user interfaces provide a user-friendly environment and adequately support the operation undertaking. The user interface layer provides graphical front-end pages to the database records, analysis result reports, task management, and the other components. Microsoft C# environment is used for user interface development. The main interface is the first displayed page when users start the application. Users log onto the system from this page to get the access to other functional pages such as data display interface and analysis system interface. To satisfy various requirements, the user interface layer can provide a widely used standard for analyzing record data and also accommodates applications developed in other programming language environment.

The interface of data display system is shown in Fig. 7. This system provides online and offline display of the sensor signals. Several display attributes can be selected by users, such as different update interval, number of visible points and data range, average number display, etc. This system would be helpful for routine operation and various studies.

4) Odor Analysis System: Odor analysis system is the key component of the software suite. The system utilizes the data analysis applications to identify rules and patterns in the data, to tell the users where is odor, how strong the odor is, to give suggestion on odor control practice, and to predict the resulted odor strength if any odor control means are applied. The data analysis system has many subsystems: odor strength analysis system calculates odor concentration/intensity using artificial intelligent techniques; odor dispersion analysis system calculates odor dispersion plume using odor dispersion models based on odor emission rates, and topological and meteorological information; risk factor analysis module identifies significant risk factors that cause odor problems; and decision-making module assists users to make odor control decisions based on analysis results and human expert knowledge. The interface of odor analysis system is shown in Fig. 8.

This analysis system also provides decision support for farmer’s odor control practice. In the analysis system, the sensor fusion algorithm and odor dispersion algorithm calculate the odor dispersion, display the odor plume dispersion in real time, and predict the odor map if any environmental factors are changed or different control means are applied. Based on odor plume prediction results, the analysis system would provide suggestions on possible odor control practice based on farmstead, topography, and meteorological data, such as when to spread manure, change vent direction, and where to plant trees to block odor. The odor dispersion analysis system provides an overall odor mapping around live facilities that is necessary for an overall odor management strategy. This will help the livestock producers to make strategic funding decisions by investing only on efficient odor control practice.

To validate the developed hardware and software system, a series of experimental studies is conducted in laboratory using odorous gases with single or multiple odor components. The results show that the developed system is functional and effective in remote data collection, wireless data transmission, and real-time display and analysis of odor data. Simulation studies on the odor dispersion model show its feasibility to model the dynamic odor dispersion around livestock farms.
III. DISCUSSIONS

The proposed e-nose-based wireless network approach to automatically monitor livestock farm odors differs from any existing e-noses in the following ways.

1) The developed wireless e-nose network system can provide multilocation odor monitoring while existing e-noses can only provide odor monitoring at a single location. Odor concentration changes with source configuration (shape of the source, building geometry, etc.), landscape around the farm, and distance to the source. The proposed wireless e-nose network system can provide a more comprehensive odor plume profile than a single e-nose system.

2) By using this wireless e-nose network system, users can monitor the odor from a remote location such as inside a house or office, so that they do not have to stay in the field, which makes odor measurement easier in unfavorable weather.

3) The developed e-nose network system with multiple e-noses is more robust to sensor failure and noise. One or more failed or incorrect sensor reading could be corrected through the redundant information from the other e-noses.

The developed wireless e-nose network system is a useful tool in remote monitoring of livestock farm odor, which will greatly improve the efficiency of livestock farm odor reduction, and thus benefit livestock industry. In addition, it would be used for prediction of upcoming odor plume profile with weather information forecast, and planning upcoming odor management.

IV. CONCLUSION

The design of an e-nose-network-based livestock farm odor monitoring system was presented in this paper. The system is composed of e-noses that can measure odor compounds and environmental factors. The e-noses are deployed in and around the farm and odor data are collected via wireless communication. The data processing algorithms and odor dispersion algorithm in the analysis system calculate the odor dispersion, display the odor plume dispersion in real time, and can also predict upcoming odor plume with upcoming weather forecast.

The main contribution of this research include the following: 1) an e-nose-based wireless network is developed for monitoring livestock farm odors; 2) data acquisition and data processing software is developed for collecting and processing odor data from the wireless e-nose network; 3) a neural-network-based odor dispersion model is proposed for modeling odor dispersion downwind of the odor source in real time; and 4) a data analysis software with user-friendly interface is developed for assisting end users in making efficient odor management decisions.

The proposed e-nose network approach can automatically monitor livestock farm odors, and have many potential industrial applications. The developed wireless e-nose network system can perform remote multipoint odor monitoring, and the integrated software suite provides data analysis capabilities that would assist users’ decision making on odor control practice. It enables more efficient odor control capabilities by providing automated, robust, and comprehensive information about the environment and odor profile in and around the livestock farms.

REFERENCES


