1 **Design and Performance Evaluation of the Upgraded Portable** 2 **Monitoring Unit for Barn Air Quality**

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8 **Abstract**

9 The Portable Monitoring Unit (PMU) was originally developed and used for measuring ammonia
10 (NH₃) and carbon dioxide (CO₂) concentrations and emissions from poultry facilities. Its use entailed a
11 substantial degree of manual setup and data processing, making field deployment of multiple PMUs a
12 logistical challenge. The original commercial electro-chemical (EC) sensor for NH₃ is no longer
13 commercially available. Thus, an effort to upgrade the PMU design was undertaken. A substantial
14 redesign of the PMU system is reported in this paper, including the data acquisition and control system
15 (DACS), and the circuit and tubing systems. A new NH₃ EC sensor was selected by an evaluation of
16 existing commercial sensors, followed by further tests to characterize its accuracy and limitations. The
17 performance of the upgraded PMU (iPMU) was evaluated from field measurements taken in a
18 commercial laying hen barn and subsequent laboratory reassessment. Results demonstrated the
19 feasibility of iPMU, making multiple-point measurements for air quality in large-scale barns practical.

20 Keywords: Emission, Concentration, Ammonia, Carbon dioxide, Animal Buildings

21 **1. Introduction**

22 The measurement of air contaminant (e.g. NH₃) concentration and emission from animal housing
23 generally requires setting up several instruments for multi-point sampling corresponding to the
24 ventilation system of the building (e.g. Li et al., 2005). The measurement instruments are required to be
25 accurate, portable, stable and affordable. The Portable Monitoring Unit (PMU) was designed and
26 developed for measuring NH₃ and CO₂ concentrations and emissions from animal buildings (Xin et al.
27 2002; Gates et al. 2005).

28 The PMU system utilized electro-chemical (EC) sensor technology (Drager PAC III) for NH₃
29 concentration measurement, which substantially reduced the system cost compared with other
30 approaches (e.g. photo-acoustic ultrasonic or chemiluminescence technologies). EC sensors will
31 saturate when continuously exposed to NH₃ gas (signal generally drifts upward, and sensor loses
32 sensitivity, effectively losing accuracy), and the PMU design overcame this weakness by creating a
33 periodic “fresh air” purge cycle with a solenoid controlled by an adjustable on-off cycle-timer (Gates et
34 al., 2005; Xin et al., 2002). In this approach, the barn air was first sampled for measuring NH₃
35 concentration and other parameters, and then fresh air was used for purging the EC NH₃ sensor and
36 allowing the sensor head to refresh. By contrast, the CO₂ sensor (Vaisala Model GMT 220, Vaisala Inc.,
37 Louisville, CO, USA) was based on infrared (IR) absorption of CO₂ with stated accuracy of 1.5% of
38 range + 2% of reading. IR measurement technology is not affected by issues of saturation as
39 encountered in the NH₃ electrochemical method. In addition to NH₃ and CO₂, the PMU also measures
40 the air temperature with a thermistor (Model TMC6-HD, Onset Computer Corp., Bourne, MA, USA)
41 and static pressure difference with a pressure sensor (Model 264, Setra Systems, Inc., Boxborough, MA,

42 USA). The reliability of the PMU was demonstrated by comparing the measurement results to same
43 certified reference NH_3 gas with a calibrated chemiluminescence NH_3 analyzer (Model 17C,
44 Thermo-Environmental Instruments, Franklin, MA, USA) (Xin et al., 2002).

45 After its development, the PMU was widely applied to measure NH_3 and CO_2 concentrations and
46 emissions in poultry houses (e.g. Li et al., 2005; Liang et al., 2006; Xin et al., 2009; Gates et al., 2008;
47 Topper et al., 2008; Casey et al., 2010). Liang et al., (2005) deployed PMUs to measure NH_3 emissions
48 from 10 commercial layer houses (6 high-rise and 4 manure-belt houses) in Iowa and Pennsylvania.
49 The results showed the NH_3 emission was influenced by different house structure, manure handling
50 scheme, diet nutrition management and geographical position. Similarly, Wheeler et al. (2006) applied
51 the PMU to measure the NH_3 emissions from 12 commercial broiler houses, representing different
52 building construction styles and manure management (built up or new litter each flock) and climatic
53 conditions (cold or mixed humid). Two major inconveniences emerged during using the PMU in field
54 measurement: 1) a manually adjusted on-off timer was used for switching between sampling and
55 purging operation; this was difficult to manually set in a coordinated way when multiple PMUs were
56 being used, and 2) a tedious process of manually downloading and processing data from different
57 sensors and data loggers. These two inconveniences required a substantial amount of time during and
58 after each test and decreased the efficiency of the measurement process. Another primary reason for
59 upgrading the PMU was that the NH_3 sensor (Dräger PAC III) was not commercially available any
60 more. A new eligible NH_3 sensor was desired to replace the PAC III sensor for measuring NH_3
61 concentration.

62 The objectives of this study were to 1) upgrade the original PMU to an intelligent PMU (iPMU)

63 with a data acquisition and control system (DACS), redesigned circuit and tubing systems, and a new
64 commercially available EC NH₃ sensor, and 2) evaluate the field performance of the iPMU in a
65 commercial laying hen barn. The various components of the original PMU (CO₂ sensor, power supply,
66 pump, solenoids, flow meters, backplane, tubing, thermistors, enclosure, etc.) were retained.

67 **2. Upgrading of the PMU**

68 **2.1 DACS Redesign**

69 The main objective of DACS redesign was to develop a user-friendly PMU system for field
70 measurement including reducing the manual operations for operating the PMU and processing the
71 measured data from the data-loggers. The new DACS was also designed to provide real-time data
72 processing, display and wireless data transfer.

73 The iPMU control system was configured with a microprocessor (Model Mega 2560, Arduino,
74 Ivrea, Italy) and several extension modules. A real-time clock (RTC) module (Model DS3231 AT24C32,
75 Dallas Semiconductor, Dallas, TX, USA) was used as a time reference. A wireless SD memory module
76 (Arduino, Ivrea, Italy) was installed to provide on-board data logging and wireless data transfer
77 (2.4GHz XBee®, Series 1, 1 mW trace antenna, Digi International Inc., Minnetonka, MN, USA). An
78 LCD screen (Serial 2004 20×4, Sainsmart, Lenexa, KS, USA) displays real-time results such as system
79 status, time, gas sensor concentrations, air temperature and static pressure difference. The control
80 system was assembled into a mini protective case (Model NBB-10260, Bud Industries Inc., Willoughby,
81 OH, USA) placed inside the larger iPMU enclosure.

82 Current output from sensors was transformed to a 0-5 Vdc signal by adding a 220 Ω resistor
83 between current source and ground. Voltage signals were read by the analog to digital converter (ADC,

84 10-bit) of the Arduino. The general relation between digital “counts” and the analog voltage is
85 (Equation 1):

$$86 \quad V = \frac{A}{1023} \times 5 \quad (1)$$

87 Where:

88 V = voltage (Vdc)

89 A = digital count

90 $1023 = 2^{10} - 1$ (number of discrete counts for 10-bit ADC)

91 5 = full scale ADC voltage range (Vdc).

92 The sensor voltage readings were converted to appropriate physical units (temperature, pressure,
93 concentration) by using appropriate calibration relations and physical laws. Details are provided in Ji
94 (2015).

95 2.4 Circuit and Tubing Systems

96 The circuit and tubing systems of the iPMU are shown in Figures 1 and 2. The iPMU consists of 3
97 subsystems: a) Sensors, b) iPMU control system, and c) Sample gas control system. Each component
98 belongs to one of the 3 subsystem, as indicated in Figure 1. Similar to the original PMU system (Gates
99 et al., 2005), the air pump was placed upstream of the sensors to minimize the leakage problems. Three
100 flowmeters were used to adjust flow to the sensors, and provide a regulated bypass. A single 3-way
101 solenoid valve (Type 6014, Burkert Contromatic Corp., Charlotte, NC, USA) controlled by DACS was
102 used to periodically switch the tubing system between barn air and purging air. A second 3-way
103 solenoid valve was added to control the tubing system during pre-sampling (Solenoid II in Figure 3).
104 This pre-sampling control feature was added to bring barn air into the tubing just before measuring,

without exposing the EC sensor to NH_3 . The solenoids were activated using a two channel solid state relay (Model SR-900, Sainsmart, Lenexa, KS, USA) controlled by the microprocessor digital outputs. The scenario of periodic measurement was determined to be 3 min pre-sampling, 2.5 min sampling and 54.5 min purging in our study (Figure 3), of which the pre-sampling and purging can be adjusted depending on the distance between iPMU and sampling points in field measurement.

Figure 1. Circuit connections of the upgraded iPMU. Each dashed blue rectangle represents a subsystems for a) Sensors, b) iPMU control system and c) Sample gas control system.

Figure 2. Tubing connections used in the iPMU. Solenoid I is used to switch between barn air or ambient air during regular operation. Solenoid II was added to draw barn air into the sample lines without exposing the EC sensor to NH_3 prematurely (pre-sample circuit). The three flowmeters adjust flow to the NH_3 and CO_2 sensors, and provide a regulated bypass.

The functions of the iPMU, including periodically measuring the barn air, purging the NH_3 sensor, data logging, and real-time data processing and display, were implemented by a program uploaded on the microprocessor through the software (Arduino IDE 1.5.5, Arduino, Ivrea, Italy). When the iPMU is powered on, the program automatically starts and follows the logic in the flowchart indicated in Figure 3. The program could also be interrupted by wireless control commands sent from computer to the wireless module, such as “Download Data”, “Delete Data”, “Reset the system”, etc. The real-time data processing algorithm was designed to be invoked when the NH_3 sensor returned stable readings (difference between two readings is less than 0.02 V), and took the average of the stable readings to return an estimated real-time measurement result of NH_3 concentration during the measuring period.

2.5 Cost of the iPMU

The components list in Xin et al. (2002) provides a useful reference, and with the list of important

130 components in the iPMU (Table 1), can be used to replicate the iPMU. Cost of several components
131 retained from the PMU system were not listed in Table 1, including power supply, flow meters,
132 backplane, tubing, and enclosure, etc.

133 2.6 EC NH₃ Sensor Replacement

134 EC sensors measure the NH₃ concentration by quantifying the electro-chemical or oxidation
135 reactions between the measured gas and the organic ingredients (e.g. organic gel electrolyte mixture) in
136 the sensor (Henderson, 2009). The potential variation during the reaction can be detected and processed
137 as a voltage output corresponding to the NH₃ by the sensor. However, the reaction rate and potential
138 variation will be unstable during longtime measurements after an initial stable phase, which will lead to
139 accumulated error in the measured data (Wilhelm, 1999). The EC sensor head has a limited lifespan
140 that expires after all of its reactant reacted (Henderson, 2009). Therefore, designing the periodic
141 purging system was necessary to maintain measurement reliability and extend the sensor lifespan in
142 field application.

Figure 3. Program flowchart.

Table 1. List of major components in iPMU

Item and Component	Model Num., Manufacturer & Address	Unity Price (\$)	Quantity	Subtotal (\$)	
DACS Control Box	Arduino Microprocessor	Mega 2560 R3, Arduino, Ivrea, Italy	45.95	1	45.95
	RTC Module	Model No. DS3231 AT24C32, Dallas Semiconductor, Dallas, TX, USA	6.99	1	6.99
	LCD screen	SainSmart LCD Module For Arduino 20 X 4, Sainsmart, Lenexa, KS, USA	14.14	1	14.14
	Wireless SD Shield	Arduino Proto Wireless SD Shield, code A000065, Arduino, Ivrea, Italy	25.47	1	25.47
	X-Bee Radio Transmitter	2.4GHz XBee®, Series 1, 1 mW trace antenna, Digi International Inc., Minnetonka, MN, USA	26.95	2	53.90
DACS subtotal				\$94	
2 Channel SSR Module	SainSmart 2 Channel SSR 5A DC-DC 5V-220V, Sainsmart, Lenexa, KS, USA	18.50	1	18.50	
3-way Solenoid Valve	Type 6014, Burkert Contromatic Corp., 2915 Whitehall Park Dr., Charlotte, NC, USA	99.99	2	199.98	
Pressure Sensor	Model 264, Setra Inc, Boxborough, MA, USA	190.00	1	190.00	
Temperature Sensor	TMC6-HD thermistor, Onset Computer Corp, Bourne, MA, USA	39.00	1	39.00	
CO ₂ Sensor	Model GMT 220, Vaisala Inc., Louisville, CO, USA	637.50	1	637.50	
NH ₃ Sensor	HONEYWELL EC FX NH3 100PPM, Honeywell Analytic, Lincolnshire, IL, USA	950.00	1	950.00	
Air Pump	SPP-6GAS-101, Gast Manufacturing, Inc., Benton Harbor, MI, USA	325.00	1	325.00	
Instrumentation subtotal				\$2360	
Total cost:				\$2454	

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148 A periodic purging system alternately exposes the sensor to NH₃ for measuring and purging the
 149 sensor with fresh air to enable the reaction to return to its initial phase. This maintains a stable reaction
 150 rate and potential variation during the measuring period. This scenario will provide discontinuous (e.g.
 151 1 h interval) measured data that are acceptable for long-term (e.g. 48 h) deployment in animal
 152 buildings.

153 NH₃ EC sensors were evaluated with three criteria:

- 154 • **Response Time ($t \leq 100$ s):** The response time is defined as the time needed by the EC sensor
 155 for detecting NH₃ concentration and returning stable readings after a step-change in NH₃

concentration. The theory of dynamic response is applied to provide more reliable analyzing of the sensor's response time (Doebelin et al., 2007). For the EC sensor, the response time can be quantified by a time constant (τ) for linear systems (Equation 2). The standard for acceptable response time was taken to be $t (=3 \tau) \leq 100$ s in the evaluation.

$$X(t) = 1 - e^{-t/\tau} \quad (2)$$

Where

t = the time after the sensor has been exposed to NH_3 gas (s)

τ = time constant, indicates the response speed of the sensor.

$X(t)$ = a time-dependent, dimensionless response value (range 0:1), representing the response to a unit step function:

$$X(t) = \frac{V(t) - V(t=0)}{V(t_{\max}) - V(t=0)} \quad (3)$$

$t_{\max}$ = time at which sensor is at a new steady-state concentration

- **Uncertainty (± 5 ppm, or less):** The uncertainty was defined as the standard deviation of the difference between sensor and reference value, for repeated measurements of a reference NH_3 gas. The standard of acceptable uncertainty was set to less than ± 5 ppm in the evaluation.

- **Stability (± 5 ppm, or less):** The sensor stability was defined as the standard deviation between the measured results over a 48 h interval with purging for the sensor to recover its initial reaction phase. The standard of acceptable stability was taken as less than ± 5 ppm in the evaluation.

To evaluate and select NH_3 EC sensors with the criteria above, the DACS of iPMU was used to setup the laboratory test. Three reference NH_3 gases with different concentrations ($24.3 \pm 1\%$, $54.0 \pm 2\%$ and $99.3 \pm 2\%$ ppm) were connected to the sample gas (Barn Air) inlet, while the room air was

connected to the purge (Ambient Air) inlet of the iPMU (Figure 3). Four sensors from different manufacturers which can provide signal output (Environmental Sensors Company Model ZDL-800; Aeroqual Series 300 Monitor with Sensor Head; MQ137 Ammonia Detection Sensor Module and Honeywell EC-FX-NH3) were evaluated. The sensors' evaluation mainly had three procedures: 1) preliminary evaluation of response time; 2) sensor calibration and 3) longtime (48 h) periodic measurement. The specific of procedures are described below.

2.4.1 Preliminary evaluation of response time

The 24.3 ppm reference NH₃ was applied and connected to the Barn Air inlet of iPMU. NH₃ EC sensors were separately connected into the system as shown in Figure 3. The flow rate was adjusted to the level recommended by the manual (0.3 lpm). During preliminary evaluation, iPMU was controlled manually (wireless communication with computer) to switch between sampling and purging. The system kept sampling until the sensor reached its stable status (variance between two continuous signal outputs is $\leq 1\%$ within 10 s). The time used for reaching the stable status was recorded as the sensor response time. Each sensor was evaluated with 5 replicate tests, with 30-60 min purging after each sampling period. The length of purging time was dependent on the accuracy recovering efficiency. The average of response time from 5 replications was used as the preliminary evaluation result for response time, initially this was set to 5 min and later based on results, 100 s.

Table 2 lists the information from sensor's evaluation and their data sheets. Only one NH₃ EC sensor (HONEYWEL EC-FX-NH3) return satisfactory result, with $\tau < 20$ s. Therefore, the other three sensors were rejected, and further studies on the HONEYWEL EC sensor were performed.

Table 2. Preliminary evaluation of EC NH₃ sensors' response time

Sensors	Time Constant, τ (s)
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Environmental Sensors Company Model ZDL-800	≥ 400
Aeroqual Series 300 Monitor (S-300)	No Response
MQ137 Ammonia Detection Sensor Module	≥ 200 & Only response to ≥ 10 ppm NH_3
Honeywell EC-FX-NH3 (0-100 ppm)	≤ 20

199

200 2.4.2 Sensor calibration

201 The signal output from HONEYWELL EC sensor is current (4-20 mA), and was transformed to
202 voltage (0.88-4.4 V) by inserting a 220 Ω resistor between the GND and SIG port of the sensor. To
203 convert the signal output from the HONEYWELL EC sensor to NH_3 concentration, the relationship
204 between voltage reading and three certified gas concentrations was established, and the linearity of the
205 relationship was checked. Normal air and the three reference NH_3 gases were applied in the calibration.
206 Three replicates of periodic measurement with 2.5 min sampling versus 57.5 min purging (30 s data
207 logging interval) were made for each certified NH_3 concentration.

208 During sensor calibration, voltage data were recorded, and the max 3 readings of each replication
209 were defined as the stable readings of the sensor as shown in Figure 4 (example with 99.3 ppm NH_3).
210 Accuracy recovery occurred at the beginning of each purge period after sampling either 54.0 or 99.3
211 ppm reference NH_3 gas. It generally took about 20-30 min of exposure to fresh air to return to
212 reasonable near-zero readings. Therefore, purging the sensor is necessary, especially when measuring
213 high NH_3 concentration.

Figure 4. Sensor data collected by periodic exposure to certified NH_3 gas. Note the need for purging to provide time for the sensor to recover.

The stable voltage readings obtained during sampling with each NH_3 reference gas were averaged and defined as the signal output from the sensor. The average signal output during purging was defined as the sensor signal output to normal air. Linear regression was performed with four points (delta value of signal output to 0, 24.3, 54.0 and 99.3 ppm) as shown in Figure 5.

Figure 5. Linear regression in calibration

The parameters obtained from linear regression were used to derive the transfer function between voltage readings and gas concentrations. Standard error of the linear regression and transfer function was calculated to evaluate the performance of the linear relationship, and are listed in Table 3. The nonlinearity between predicted results at reference concentrations were calculated (“uncertainty” in Table 3), and fell within the acceptable uncertainty range.

228

Table 3. Results of sensor calibration

Specifics (units)	Sensor Calibration
Linear Regression (LR)	$Y = 0.040 X - 0.007$
Std.Error of LR (V)	0.136
Conversion Equation (CE)	$X = 25.253 Y - 0.178$
Std.Error of CE (ppm)	3.4
Uncertainty at 25 ppm (ppm)	-0.2
Uncertainty at 50 ppm (ppm)	-2.2
Uncertainty at 100 ppm (ppm)	+3.8

229 *2.4.3 Long-time periodic measurement*

230 To determine a reasonable purging time, 48 h long-time periodic measurements were taken with
231 the same three certified reference NH_3 concentrations. The control system was setup to automatically
232 switch working status (sampling or purging). The manufacturer recommends that the sampling time for
233 the EC sensor be less than 2.5 min. However, to anticipate a possibility of overloading of NH_3 during
234 field use, the sampling time was set to be 8 min with 52 min purging, with a 30 s sampling interval
235 during measurement.

236 Similar to sensor calibration, the max three readings in each sampling period were selected as
237 representative stable concentration readings. The average and standard deviation of stable readings
238 were calculated (listed in Table 4). The standard deviations ranged from 0.8 to 2.6 ppm, which
239 indicates the stability of accuracy was acceptable during the long-time measurement. Therefore, the
240 long-time measurement stability of the EC sensor was satisfactory for upgrading the PMU system
241 when applying 8 min sampling versus 52 min purging as the scenario, and a 1 h interval periodic
242 measurement was therefore established as a basic design.

243

Table 4. Results of the long-time measurement

Measured concentration to	Measurement Results (ppm)
$24.3 \pm 1\%$ ppm reference NH_3	21.8 ± 0.8
$54.0 \pm 2\%$ ppm reference NH_3	61.6 ± 2.0
$99.3 \pm 2\%$ ppm reference NH_3	100.0 ± 2.6

251 To use a 1 h interval scenario, the sensor response time during the sampling period must be
 252 quantified to accurately determine when the sensor achieves stable status and provides meaningful
 253 results, so that real-time processing can be developed in DACS programming. By applying dynamic
 254 response theory (Doebelin et al., 2007), measured data (converted to gas concentration) during the first,
 255 middle and last 1 h sampling period of the 48 h measurement were selected, processed by dividing by
 256 the measurement results (Table 4), and expressed as percentage of sensor response, as shown in Figure
 257 6 (an example with nominally 100 ppm NH₃ calibration gas).

252
 254 **Figure 6.** Representative plots of dynamic response during first, middle and last hour of the 48 h measurement. Note the steady
 255 decay in the stable response portion of the sampling interval, as noted by the points marked with “x”.

259 The time to reach 95.0% of the final measurement results is equal to the response time of sensor
 260 with 3 time constants (τ). The 3τ response times during the first, middle and last 1-h sampling period of
 261 the 48 h measurement for each of the three NH₃ concentrations are listed in Table 5. The average 3τ
 262 response times was defined as the accurate response time of the sensor during the sampling period, and
 263 is about 1 min.

260 **Table 5.** Results of response time based on long-time measurements

Sampling period	Time to 95% response (s)
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	100 (99.3) ppm gas	50 (54.0) ppm gas	25 (24.3) ppm gas
[0-1 h]	60	60	60
[23-24 h]	60	60	60
[47-48 h]	60	60	60
[Average]	60 ($\tau=20$)		

By comparing the first, middle and last 1 h of data (Figure 6), a total of nine stable readings were provided by the sensor at the beginning, indicating approximately 3 min of stable status during the sampling period. However, after 24 h of periodic measurement, only 3 stable readings (1.5 min stable status) were obtained from the sensor before its signal began to drift with an obvious decline. Finally, in the last 1 h sampling period the stable status was only 1 min (2 stable readings). The decrease of a stable status time over the course of the 48 h measurement indicated sensor saturation, which can only be recovered with long-time purging after periodic measurement, and cannot be recovered when the sensor head exceeds its lifespan. To conserve the sensor during sampling, a 1.5 min stable status was selected, and the sensor was purged after 1.5 min stable status in each cycle (sampling and purging) of periodic measurement.

Therefore, by adding 1 min response time, the finalized sampling time was 2.5 min (1 min response and 1.5 min stable status), which matches the recommendation by the manufacturer for exposure during calibration. The scenario of periodic measurement was determined to be 3 min pre-sampling, 2.5 min sampling and 54.5 min purging, of which the pre-sampling and purging can be adjusted depending on the distance between iPMU and sampling points in field measurement.

3. Performance Evaluation of iPMU

The iPMU with new NH_3 sensor, DACS design and circuit and tubing system were evaluated by field measurement and subsequent laboratory reassessment. A caged layer barn, with manure belts in a commercial egg farm in the Midwest USA was chosen for the field test. The layer barn is 540 ft

(164.59 m) long × 91 ft (27.75 m) wide with 2 floors (12 tiers of cages), and about 425,000 laying hens.

The laboratory evaluation was a comparison of the NH₃ sensor performance to the same reference NH₃ gas before and after field measurement, and indirectly assessed the reliability of the sensor during field measurement.

3.1 Field measurement

The fan placement for the ventilation system of the barn is illustrated in Figure 7. Minimum ventilation fans on the barn's southwest side were selected as the sampling points. The field measurement was performed over a 48 h period aimed at evaluating the DACS performance. Evaluation included periodic control, signal communication with sensors, data logging, real-time processing and wireless data transfer. Before the test, the sensors were calibrated, the circuit and tubing connections were rechecked, and the protective case was disinfected.

Figure 7. Barn ventilation system

After 48 h, the measured data were downloaded wirelessly from the iPMU. Forty-eight series of sampling data were obtained by the system, demonstrating the DACS successfully implemented different functions during the measurement. NH₃ concentration was recorded as voltage data, as well being processed in real-time and presented as concentration on the LCD screen. The downloaded

303 voltage data were post-processed and converted to gas concentration. The processed data of the field
304 measurement are plotted in Figure 8. The post and real-time processed data of NH_3 concentration are
305 plotted in Figure 9. The linear regression between post and real-time processed data had 94.5%
306 consistency with 11.6 ppm offset, which was caused by inaccurate boundaries in the real-time
307 programming to recognize stable readings. It was subsequently fixed to provide real-time processed
308 data equivalent to post-processed data. The real-time processing algorithm can be optimized to provide
309 more reliable real-time processed data.

304
305 **Figure 8.** Processed data of the field measurement. Vertical bars represent standard errors.

306
307 **Figure 9.** Real-time versus post processed data. The discrepancy in real-time processing was corrected subsequently.

3.2 Subsequent laboratory reassessment

To evaluate the reliability of NH₃ EC sensor after completing a 48 h field test, a subsequent 12 h laboratory reassessment was performed with same reference NH₃ gas. The 12 h data were processed with same method as used for the previous 48 h field measurements.

The difference between previous measurement results and the laboratory evaluation results upon return were calculated, which were all contained in acceptable uncertainty range. Moreover, a linear regression of the 12 hourly average concentrations over time was done to test whether a significant linear drift occurred (the slope parameter β was tested for significance). The specifics of the analysis are listed in Table 6. The T test null hypothesis was that the slope β is zero, indicating the stability of the sensor was satisfactory with 95% confidence during the 12 h measurement. Therefore, the sensor performance was confirmed to be acceptable in terms of uncertainty and stability, as it was before the field measurement, and the reliability during the field measurement could be approved.

Table 6. Specifics of laboratory evaluation upon return

Analyzing results	12 h reassessment
Mean of 99.3 ppm in 12 hours test (ppm)	101.00
Difference from previous measured results (ppm)	+1.0
95% T test result ^[a] (reject H0 or accept H1)	H1
Drift (Slope of LR)	~0
Mean of 54.0 ppm in 12 hours test (ppm)	61.8
Difference from previous measured results (ppm)	+0.0
95% T test result (reject H0 or H1)	H1
Drift (Slope of LR)	~0
Mean of 24.3 ppm in 12 hours test (ppm)	22.8
Difference from previous measured results (ppm)	+1.0
95% T test result (reject H0 or H1)	H1
Drift (Slope of LR)	~0

^[a] Test H0 : $\beta = 0$ vs. H1 : $\beta \neq 0$ at the 5% level of significance.

320 **4. Conclusions and Recommendations**

321 The upgrade of the PMU system was completed by redesigning the DACS and the circuit and
322 tubing systems, and replacing the obsolete NH₃ EC sensor. The estimated overall cost to build the
323 iPMU is about \$2,500 (Table 1). Results of field testing and subsequent laboratory reassessment
324 demonstrated the utility of the iPMU for monitoring gas (NH₃ and CO₂) concentration and emission in
325 animal housing. The iPMU provides an economical and practical method for single or multiple-point
326 measurement of barn air quality.

327 Future improvements recommended include: 1) reduce the periodic measurement interval, with
328 less purging time; 2) optimize the real-time processing algorithm to provide more reliable real-time
329 processed data; 3) replace the protective enclosure with a smaller size to further enhance the portability
330 of the system; and 4) upgrade the wireless communications to enable longer distance data transfer.
331 Moreover, the performance of the selected EC sensor should be evaluated for effects of gas
332 cross-interference (e.g. methane) to guarantee the accuracy when measuring complex barn air.

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