An Internet of Things system to monitor environmental conditions in livestock housing

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Abstract

Environmental factors in livestock housing are getting increasing attention due to the need to maintain an adequate condition for animal welfare and to account for the emissions of pollutants. For this reason, an IoT system has been developed and implemented in different livestock housing (pigs, dairy cows, and rabbits). The system is based on nodes that integrate all the necessary electronics and implement the firmware to perform three main functions: raw sensor measurements, local data processing, and data transmission to a gateway. The gateways are hardware/software systems powered by the mains (220V; indoor gateway) or by a solar panel and a backup battery (outdoor gateway). Data is sent to a dashboard presenting all sensor data.
The main node developed for environmental monitoring is connected to sensors for: ambient temperature and relative humidity, light intensity, sound pressure, carbon dioxide, ammonia, hydrogen sulfide, particle matter concentration, and volatile organic compounds. The usefulness of the data recorded by the device for the assessment of suitable conditions for the animals have been reported. In particular, in a rabbit housing, the scarce uniformity of the ventilation system has been highlighted by high ammonia concentrations and some hotspots. The recordings in a pig farm have shown a daily pattern in the concentrations of CO_2 and ammonia due to the farm operations, giving indications that the feed delivery is the most critical one. The application in a dairy farm has demonstrated the feasibility of a continuous monitoring of ammonia emissions with the use of the developed device.

Keywords: animal welfare, gas concentrations, ammonia emissions, ventilation

Introduction

A proper environmental condition in livestock houses is essential to assure animal welfare and productivity (Qi et al., 2023). The attention to environmental factors is increasing also in relation to climate change. In particular, the increase of temperature can negatively affect the performances of the animals (Ji et al., 2020; Lee et al., 2016; Qi et al., 2023). The main factors considered are temperature, humidity and in some case air velocity, but the environmental conditions in livestock housing should also include factors like light intensity, gas concentrations, and noise levels. For these factors, only in some cases, limits and optimal levels are defined, but it is well known that can affect animal welfare.

For this reason, devices to monitor environmental conditions have been developed and proposed on the market. In the field of Precision Livestock Farming, the monitoring device for environmental conditions must be also able to integrate the recordings with other data collected in the livestock housing and arriving from the animals using wearable sensors or other devices (Leliveld and Provolo, 2020).
The experience carried out by Leliveld et al. (2024) demonstrate the feasibility of this approach and led to the development of an IoT system for dairy cow farms. However, the need for a suitable multipurpose device to monitor environmental conditions in livestock housing clearly emerged. For this reason, an IoT device able to record the main climatic parameters and gas concentrations has been developed and installed in different livestock housing to record environmental conditions and obtain an assessment on the adequateness to animal requirements.
This paper describes the device developed and reports its application in three case studies to show the applicability of the system to different animal housing.
The first case is a rabbit farm where the objective was to evaluate the trend and uniformity of environmental conditions in the housings. The second case study is a pig farm where the device has been used to analyze the daily fluctuations of gas concentrations, specifically in connection with management operations. The last case is related to a dairy cow farm where the continuous collection of gas concentrations has been used to estimate ammonia emissions from the barn.

Material and methods

Device for environmental monitoring
Environmental monitoring is carried out using a multi-sensor node developed by IBT Systems (Milano, Italy) in collaboration with the Department of Agricultural and Environmental Sciences of the University of Milan. The environmental sensor node, referred to as N11 in the following, is one of the several sensors initially developed for integrated monitoring of dairy cattle farms, extended and adapted for other livestock.
The N11 node is composed of four main parts:

- **Main board.** The main board hosts and connects all the components of the N11 node described in the following. Its mechanical design has been co-developed with a custom plastic housing designed specifically for the node and for the target environment.
- **Power supply unit.** It consists of rechargeable batteries and the charger control circuit, capable of operating both from a 12V DC voltage source, typically generated by a commercial power adapter connected to AC mains, and from a solar panel, through a 12V backup battery. The internal batteries can guarantee continuous operation for approximately 20/25 days.
- **Processing unit.** The processing unit is based on an ultra-low power system-on-chip providing significant processing resources (flash memory, volatile memory, and computational power) and integrating a dual-radio supporting both Bluetooth Low Energy and custom sub/gigahertz transceiver. Both radio communications are used by the node N11, BLE being dedicated to local communication with a mobile app for configuration and diagnostic purposes, while sub-gigahertz custom radio is devoted to data communication with the local gateway.
- **Sensors.** The sensors are either standard components directly connected to the main board (e.g., the particle matter sensor), or three custom expansion board designed for

the specific purpose of the measure, namely temperature, humidity and sound pressure sensor (EXP_THS), illumination sensor (EXP_LUX) and gas sensors (EXP_CHEM).
While the EXP_THS and the EXP_LUX expansion board are mainly designed to host their sensors in small PCBs, separated from the main board, to optimize their placement inside the N11 plastic case, the EXP_CHEM expansion board is a little more complex. It has been primarily designed to host a wide variety of electro-chemical sensors and to be easily pluggable onto the main board in such a way to expose the active part of the sensors to the openings in the plastic case. In addition to the amplification and conditioning electronics for the sensor signal, the board hosts a small non/volatile memory for storing identification and calibration information of the specific gas sensor mounted on the board.
Furthermore, an EXP_VOC board has also been designed as a variant of the EXP_CHEM board, to integrate a VOC sensor based on CMOS technology.
Figure 1 shows the complete sensor node in its plastic case.
For the experimentation described in this paper the N11 node has been equipped with the sensor listed in Table 1, along with their main characteristics. NH_3, CO_2 and H_2S sensors have been calibrated before use with standard gases and checked with a gas analyser (Gasmet GT 5000).

Table 1: Sensors installed in the N11 device and their main characteristics.

Sensor	Type	Technology	Range	Accuracy
Temperature	Digital	CMOS	-10 – +60 °C	± 0.2 °C
Relative humidity	Digital	CMOS	0 – 100 %	± 2 %
Sound pressure	Analog	MEMS	30 – 130 dBA	± 2 %
Illumination	Analog	ALS Photodiode	0 – 128 klux	± 30 %
H_2S	Analog	Electrochemical	0 – 10 ppm	± 10 %
NH_3	Analog	Electrochemical	0 – 100 ppm	± 10 %
CO_2	Digital	NDIR	400 – 10000 ppm	± 30 ppm / ±3 %
VOC (VOCs)	Analog	CMOSense	500 – 10000 ppb	± 15 ticks /0.03 %
VOC (NO_x)	Analog	CMOSense	50 – 650 ppb	± 50 ticks / 0.1 %
PM1, PM2.5	Digital	Laser scattering	0 – 1000 $\mu g/m^3$	± 10 $\mu g/m^3$
PM4, PM10	Digital	Laser scattering	0 – 1000 $\mu g/m^3$	± 25 $\mu g/m^3$

As the table shows, some of the sensors needs to be read as analog signals while other provide a digital interface. In the latter case, the measurement process is managed internally by the sensor logic, which only provides data at a certain frequency, selectable when the sensor is configured by the application firmware. For analog sensors, on the other hand, the measurement process is totally under control of the electronics and the firmware of the N11 node.
Considering the nature of the physical phenomenon, the characteristics of the sensors and constraints on the transmission of data to the gateway, which is scheduled at regular intervals of 10 minutes, the measures are performed as follows:

- Temperature and humidity. Sensors are read every 10 minutes.
- Electrochemical. Sensors are sampled every 10 seconds and averaged over the 10 minutes interval.

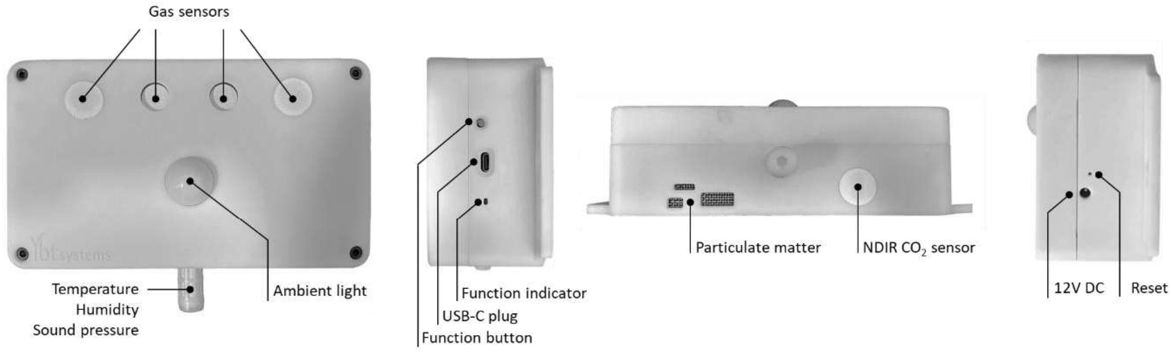

Figure 1: N11 device with enclosure

- Sound pressure. The sensor is sampled every 10 seconds and the minimum, maximum and average value is calculated for each 10 minutes period.
- Carbon dioxide and ambient light. Sensors are read every minute and averaged over the 10 minutes period.
- Particulate matter and VOC. Sensor are read every 15 minutes and sent to the gateway every 10 minutes, skipping those intervals where the measure is not yet ready and available.

Every 10 minutes, thus, the firmware collects all the available measures, computes average, maximum and minimum values and composes a single binary-encoded compact packet to be transmitted to gateway through the custom sub-gigahertz wireless channel.

Study of environmental conditions uniformity in a rabbit farm

In a rabbit fattening housing in cages hosting 4000 heads, six N11 devices has been installed at the cage level. Figure 2 show the layout of the building and the position of the devices. The monitoring has been carried out from 14/03/23 to 20/03/2023.
Data recorded by the six devices has been organised in hourly values and processed to assess the differences using the generalised linear model procedure of IBM SPSS Statistics v 29. A pairwise comparison has been used to indicate the significant differences among devices.

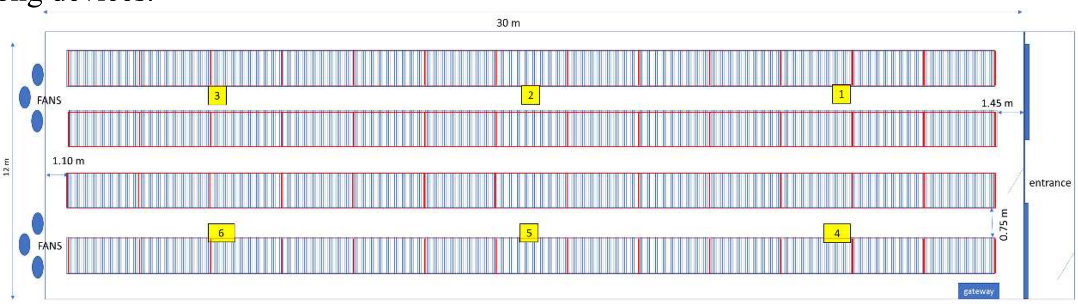

Figura 2: Scheme of the structure of the rabbit farm and position of the six N11 devices during the monitoring period.

Daily pattern in a pig farm

The recordings were carried out in the gestation room of a pig farm where the sows are raised in pens with partially slatted floor. The monitored room, relating to the second phase of gestation (after the first 4 weeks from insemination), consists in 24 pens each of 23.4 m^2 of total surface area and 9.9 m^2 of slatted floor, housing up to 10 animals each. Two N11 devices were installed in the central part of the room, at an approximate height of 2.2 m from the floor. The data reported in this work refers to a device for the period from 13/06/2023 to 9/08/2023. In particular, temperature, carbon dioxide, and ammonia were analyzed comparing the averages of each hour of the day for the whole period.

<u>Ammonia emission in a dairy cow farm</u>

The monitoring has been carried out in a livestock farm with 140 lactating cows (average milk yield 37 kg $head^{-1}$ day^{-1}) and a total of 290 heads, from 8/08/2023 to 23/03/2024. Three N11 devices have been installed in the barn for lactating cows and a further N11 device has been placed outside the barn to record background concentrations.

Cows are stabled in 4 rows of cubicles in an area of 1250 m^2. Data collected by the N11 devices has been used to estimate the emissions using the methods reported in the VERA protocol (VERA, 2018). CO_2 has been used as trace gas, calculating the production of the cows on the base of their milk production level and energy intake. NH_3 emissions have been obtained as:

$$E_{NH3} = P_{CO2}\ x\ \frac{[C_{NH3}]barn - [C_{NH3}]outside}{[C_{CO2}]barn - [C_{CO2}]outside} \qquad (1)$$

Where: E_{NH3} is the emission of NH_3 (kg h^{-1})

P_{CO2} is the production of carbon dioxide from the cows (m^3 h^{-1})

C_{NH3} is the concentration of NH_3 inside and outside the barn (mg m^{-3})

C_{CO2} is the concentration of CO_2 inside and outside the barn (ppm)

The calculation has been performed on an hourly basis, considering also the temperature in the barn, and then averaged over 24 hours.

Results and Discussion

<u>Uniformity of environmental conditions in a rabbit farm</u>

Table 2 reports the average values of the whole monitoring period of the various environmental factors measured by the six N11 devices. The significant differences between the hourly values detected by the six control units are also reported. As can be seen, the variability within the building is very high especially for gas concentrations, and, in particular, for ammonia.

Table 2: Average daily values and significance of the differences among devices for the environmental factors monitored.

Device	Temp.		UR		NH_3		CO_2		H_2S		sound		$PM_{2.5}$	
ID1	21.9	e	62.5	c	7.3	e	2,287	a	0.00	d	57.7	e	17.2	bc
ID2	22.1	d	59.8	d	6.5	f	1,998	d	0.00	d	58.8	c	18.6	ab
ID3	22.3	c	63.2	b	9.5	c	2,272	a	0.00	d	58.7	c	16.5	c
ID4	22.4	b	62.9	b	11.4	a	2,203	b	0.01	c	58.3	d	17.8	ab
ID5	22.5	a	58.1	e	7.9	d	1,945	e	0.04	a	59.0	b	17.1	bc
ID6	21.6	f	66.0	a	10.4	b	2,125	c	0.02	b	59.3	a	17.5	b

Figure 3 shows a distribution map of ammonia obtained from the average values of each device and highlights an area of the room where ventilation is not sufficient to maintain the concentration of this gas at levels lower than the 10 ppm indicated as upper limit by the guidelines for the welfare of rabbits (Italian Ministry of Health, 2021).

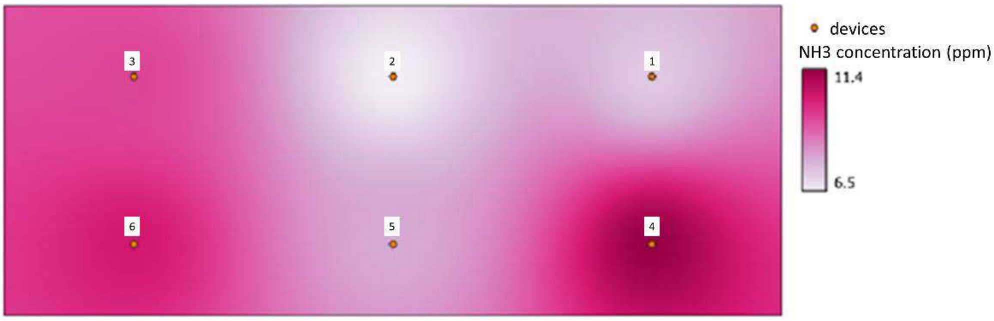

Figure 3: Distribution map of the average values of ammonia concentrations in the rabbit house

Daily pattern in a pig farm

From the analysis of the hourly average values of the factors considered it can be highlighted that two peaks in concentrations of ammonia and carbon dioxide occur during the day (Figure 4).

The highest values are found around 7 am when the feed is delivered. The afternoon peak is less pronounced and occurs around 4 pm, the time of the second feed distribution.

The higher values in the morning could be due to the greater activity of the animals at this time of the day, corresponding to illumination and temperature increase. However, there are no trends linked to temperature variations throughout the day. This is not unexpected as the temperatures are well above the optimal values for gestating sows, which typically range from 16°C to 22°C (Ma et al., 2023; Robbins et al., 2021).

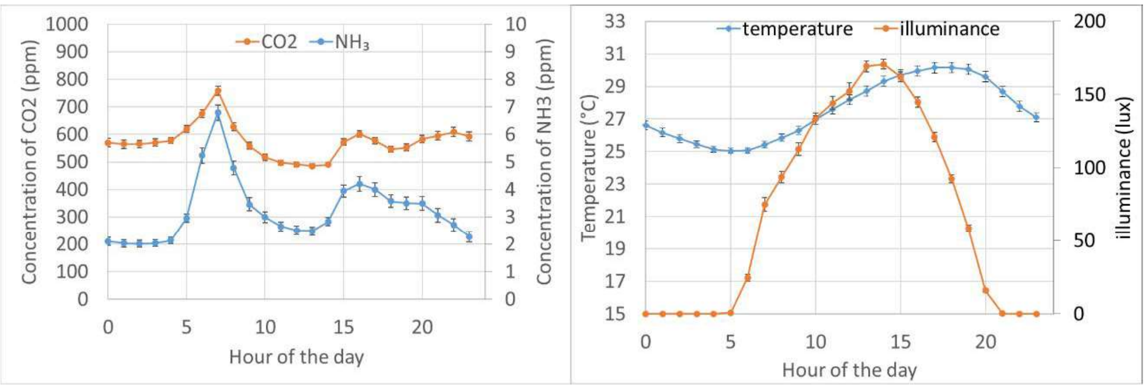

Figure 4 – Average hourly values of carbon dioxide and ammonia concentrations (left), temperature and illuminance (right) recorded in a pig farm. Bars represent the standard error.

Ammonia emission in a dairy cow farm

The results obtained from the estimate of ammonia emissions are reported, as daily values, in figure 5. As can be seen, ammonia emissions referred to dairy cows vary between 30 and 45 grams per animal per day. The values found are in line with those reported by Groot Koerkamp et al. (1998) and are affected by seasonality and temperature. The correlation with the temperature inside the barn is not significant and the effect of other factors influencing the emissions should be investigated. It should also be noted that the method used is affected by numerous uncertainties related to the accuracy of the measurement system, the representativeness of the measurements in the barn and some assumptions of the method. However, the possibility of continuously collecting data allows to understand the trend of emissions over time with equipment that can be easily installed in livestock farms. The validity of the method must also be verified in different conditions by comparing it with reference methods.

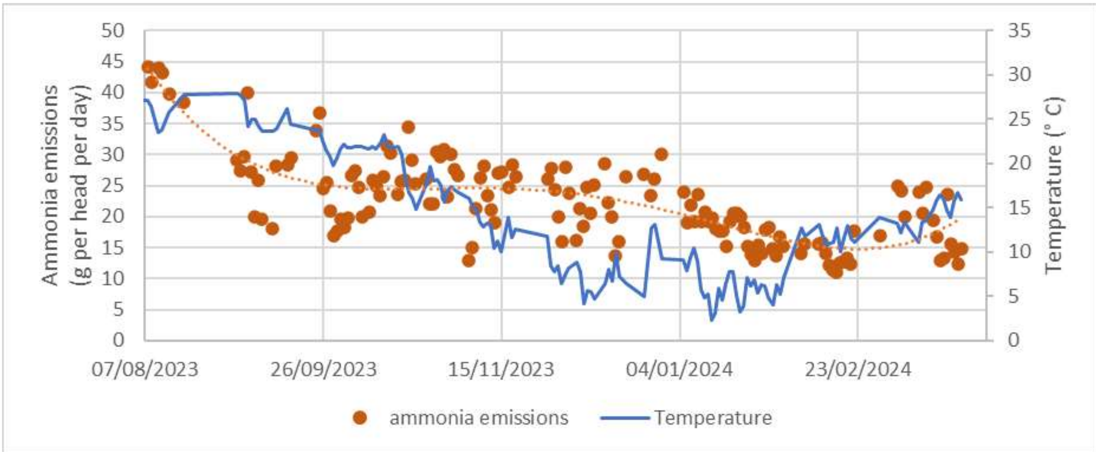

Figure 5 – Daily values of ammonia emissions and temperature in the dairy cow barn.

Conclusions

This paper describes an IoT device for environmental monitoring of livestock housing and three case studies of its implementation with different purposes in livestock farms.
The utility of the data recorded by the device for the assessment of suitable conditions for the animals have been reported. In particular, in the rabbit housing, the scarce uniformity of the ventilation system has been highlighted by an elevated ammonia concentrations inside the building and hotspots in some area. The recordings in the pig farm have shown a daily pattern of the concentrations of CO_2 and ammonia with peaks due to the farm operations, giving indications that the feed delivery is the more critical. The application in a dairy farm has demonstrated the feasibility of a continuous monitoring of ammonia emissions with the use of the device. The results obtained demonstrated that the use of the IoT device can support the analysis of the adequateness of the ventilation system, of the air quality conditions to guarantee animal welfare and of the emissions from livestock housings.

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References

Groot Koerkamp, P.W.G., Metz, J.H.M., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L., White, R.P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K.H., Pedersen, S., Takai, H., Johnsen, J.O., Wathes, C.M., 1998. Concentrations and Emissions of Ammonia in Livestock Buildings in Northern Europe. *Journal of Agricultural Engineering Research* **70**, 79–95. https://doi.org/10.1006/JAER.1998.0275

Italian Ministry of Health, 2021. Linee guida nazionali in materia di protezione di conigli allevati per la produzione di carne. Italy.

Ji, B., Banhazi, T., Perano, K., Ghahramani, A., Bowtell, L., Wang, C., Li, B., 2020. A review of measuring, assessing and mitigating heat stress in dairy cattle. *Biosystem Engineering* **199**, 4–26. https://doi.org/10.1016/J.BIOSYSTEMSENG.2020.07.009

Lee, I.K., Kye, Y.C., Kim, G., Kim, H.W., Gu, M.J., Umboh, J., Maaruf, K., Kim, S.W., Yun, C.H., 2016. Stress, nutrition, and intestinal immune responses in pigs - A review. *Asian-Australas J Anim Sci* **29**, 1075–1082. https://doi.org/10.5713/AJAS.16.0118

Leliveld, L.M.C., Brandolese, C., Grotto, M., Marinucci, A., Fossati, N., Lovarelli, D., Riva, E., Provolo, G., 2024. Real-time automatic integrated monitoring of barn environment and dairy cattle behaviour: Technical implementation and evaluation on three commercial farms. *Comput Electron Agric* **216**, 108499. https://doi.org/10.1016/J.COMPAG.2023.108499

Leliveld, L.M.C., Provolo, G., 2020. A review of welfare indicators of indoor-housed dairy cow as a basis for integrated automatic welfare assessment systems. *Animals* **10**, 1–18. https://doi.org/10.3390/ANI10081430

Ma, H., Xie, Y., Li, A., Zhang, T., Liu, Y., Luo, X., 2023. A review on the effect of light–thermal–humidity environment in sow houses on sow reproduction and welfare. *Reproduction in Domestic Animals* **58**, 1023–1045. https://doi.org/10.1111/RDA.14400

Qi, F., Zhao, X., Shi, Z., Li, H., Zhao, W., 2023. Environmental Factor Detection and Analysis Technologies in Livestock and Poultry Houses: A Review. *Agriculture* **13**, 1489. https://doi.org/10.3390/AGRICULTURE13081489

Robbins, L.A., Green-Miller, A.R., Lay, D.C., Schinckel, A.P., Johnson, J.S., Gaskill, B.N., 2021. Evaluation of sow thermal preference across three stages of reproduction. *J Anim Sci* **99**. https://doi.org/10.1093/jas/skab202

VERA, 2018. Test Protocol for Livestock Housing and Management Systems, VERA – Verification of Environmental Technologies for Agricultural Production.