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A measurement system for enteric CH_4 emissions monitoring from ruminants in livestock farming

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ABSTRACT
In this paper, a proposal for an Internet-of-Things (IoT) based measurement system dealing with the enteric methane (CH_4) emission monitoring from ruminants is presented. Herein, a brief overview of the recent advances in sensors technologies and their IoT integration for realizing measurement systems able to monitor the CH_4 emissions in ruminants is also presented. Nowadays, it is confirmed that CH_4 emissions, which are mainly produced during normal fermentation of feeds by the rumen microorganisms, are part of the Green-House Gas (GHG) emissions. Therefore, a classification of the existing measurement methods, sensing technologies and their impact on the animal's welfare is presented. The proposed measurement system, together with its sensing elements and the developed data acquisition system are also reported in this paper. A preliminary disposal and field trials of the developed system in a farm facility is given.

Section: RESEARCH PAPER

Keywords: Livestock; CH_4 measurement; IoT sensor

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1. INTRODUCTION

Methane (CH_4) is a powerful greenhouse gas, second only to carbon dioxide (CO_2) in terms of its contribution to global warming (IPCC, 2021) [1]. Methane has a Global Warming Potential (GWP) 85 times that of CO_2 over a period of 20 years, although CO_2 has an atmospheric lifetime of thousands of years, while methane disappears in about 10-15 years [1]. The rapid decay of methane and its high impact on atmospheric temperature make it a primary objective to curb in a timely and effective manner the climate change. According to the recent report of the International Energy Agency (IEA, 2021) reducing anthropogenic methane emissions is one of the most effective strategies, including in economic terms, to rapidly reduce the rate of warming and contribute significantly to efforts to limit the increasing global temperature [2].

Animal agriculture is responsible for 8 % – 10.8 % of Global green House Gas (GHG) emissions as assessed by IPCC accounting and, on the basis of lifecycle analysis, the contribution of livestock is up to 18% of GHG emissions [3]. Nevertheless, livestock farms are typically not equipped by any instrumentation suited to quantify the methane emission from animals.

On the other hand, several studies have been performed to evaluate the effect of feed on gas emissions, having the aim of allowing a continuous selection of animals [4]. In [5] and [6], a

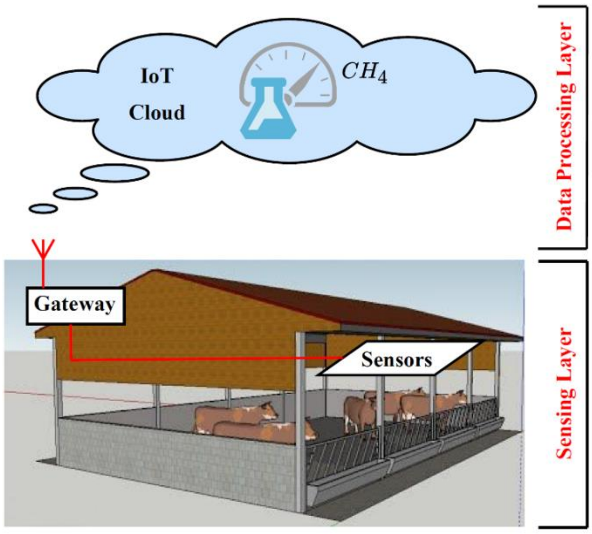

Figure 1. Generic scheme for Internet-of-Things based monitoring of enteric methane CH_4 emissions from ruminants.

review work discussing the perspectives to methane emission mitigation is presented.

In Figure 1, a generic overview of the IoT based monitoring of the CH_4 emissions from ruminants is depicted. The role of IoT based measurement systems is well described in literature [7], and the requirements in the design of an IoT based measurement system were analyzed in depth in [8]-[16].

In this paper, a brief overview of proposed technique aimed to measure the enteric CH_4 emissions in ruminants together with the description of the first hardware prototype are presented.

The choice of the CH_4 sensor was done by analysing the state-of-the-art sensing methods, which briefly are reported in the next Section. The adopted proposal considers the non-invasive way to capture the enteric CH_4 emissions in ruminants by using a metal sleeve with gas sensing holes and tubes to drive the captured gas to the gas sensor.

The paper is organized as follows. In Section II, a short overview regarding the CH_4 emissions monitoring in ruminants, measurements methods and IoT based sensors for monitoring is presented. The integration to the IoT platforms for smart livestock management is briefly introduced in Section 3, while in Section 4, the proposed monitoring system is described. Lastly, in Section 5, several conclusions and future work directions are summarized.

2. METHANE GAS EMISSION MEASUREMENT

In this section, a short overview of the literature concerning the measurement of CH_4 produced by ruminants is reported. First of all, the enteric CH_4 emissions in ruminants can be monitored by doing direct or indirect measurements. The literature describing measurement methods and sensors systems for measuring CH_4 production from ruminants is covering a wider interest nowadays and many implementation issues are discussed in [17]-[23]. Thus, according to the surveyed literature, a rough classification of the main available techniques can be provided according to following aspects:

- *Duration of the measure time windows*. Some approaches aim to collect all the daily production of the methane produced by animals. Instead, in [24] it is proposed to collect the gas emission in reduced time window (i.e., during rumination) to estimate the global emissions. In this way, by monitoring the cows ruminant behaviour using a wearable sensor, the accuracy of the enteric methane emissions could be drastically improved. Beyond the mentioned articles above, there are also several research works published in literature proposing measurement prototypes capable to real-time monitoring of the enteric methane emissions in ruminants. For example, in [25], a statistical analysis over a prototype which has been developed to measure in real-time the greenhouse gases emitted by livestock (i.e., in particular, the CH_4 and CO_2) is presented. The measurements were obtained during normal grazing conditions, thus in order to be consistent, the obtained data from measurements, the time-stamps (before and after each measurement) of the animal feedings were taken.
- *Capability to relate the emission measurement to individual animals or to group of animals*. This aspect is mainly relevant when a cross comparison has to be operated among animals in terms of genetic make-up or feeding. In [26], a prototype that has been developed for measuring the single cattle emission of CH_4 and CO_2 is presented. The prototype consists of: (i) two gas sensors (i.e., one for CH_4 and one CO_2), (ii) a transceiver, (iii) a support type structure attached to the head of the animal comprising straps that are attached to this structure, and a (iv) a battery. The main disadvantage of the proposed system in [26] is related to the existing real risk of damage of the used components due to the mechanical shocks.
- *Integration in real livestock farms*. In [27], a research study reporting experimental results from a real integration of a monitoring system for methane emission from ruminants in real livestock farms, is presented. The analysis is done adopting a Bayesian network which models the relationships among various factors that are related to the enteric methane emissions from cows.
- *Impact on animals' welfare*. For example, systems like the one presented in [28] requires that each cow is trained to use an automatic head-chamber system. Main benefits are: (i) the simplicity, (ii) non-intrusive method, and (iii) less expensive and easy way to be operated. The system described in [28] uses a Radio-Frequency Identification (RFID) system for each animal.

3. IOT FOR SMART LIVESTOCK MANAGEMENT

Internet-of-Things (IoT) technology has been proved that can make a breakthrough in livestock management by connecting biological information of livestock and environmental information obtained by IoT sensors to farmers. This is important when the farm is located in remote location and data should be transmitted in cloud for remote management [29]-[31].

For this specific case, an IoT-based system can be typically formed by [32]-[33]: (i) a physical layer (PL) known as a perception layer, managing the measurement of physical quantities that are desired to be monitored, (ii) a communication layer (CL) for data transmission/reception, and (iii) an application layer (AP) for agricultural and livestock farming applications. For example, in order to sense in real-time the greenhouses, at the PL level, the sensor nodes are mounted in various areas, like [34]-[36]: (i) farms, (ii) crops, (iii) livestocks, etc. The main sensors which forms usually a Wireless Sensor Network (WSN) are responsible to measure the temperature, humidity, soil moisture, pressure, pH, particulate matter, and not least the outdoor area (farm field) and indoor area (greenhouse) quality [37], [38]. The CL has the main role to data transmission to AL by using IoT specific telecommunications networks. However, in order to implement CL, the available solutions that could be adopted should take into account the data rate for the information quantity, distance coverage, and power consumption. Among the existing low power wide area (LPWA) technologies [39], the LoRa (long-range) and NB-IoT (narrow-band) are the two leading emergent solution. On the other hand, LoRaWAN has to be considered as the suitable candidate in low-power and small data-rate applications, while Wi-Fi should be preferred where large data throughput is desired for specific applications (e.g., visual and IR cameras). The main used protocols for IoT agricultural and livestock farming applications are: (i) the Message Queue Telemetry Transport (MQTT) protocol, (ii) the Constrained Application Protocol (CoAP), (iii) the Extensible Messaging and Presence Protocol (XMPP), (iv) the Advanced Message Queuing Protocol (AMQP), (v) the Data Distribution Service (DDS) protocol, (vi) the Representational State Transfer Hypertext Transfer Protocol (REST HTTP), and (vii) the WebSocket protocol. In [40], it is shown that in most cases MQTT outperforms the other IoT protocols, while the use of CoAP protocol can be considered as the next best option since it attains very promising performance in most network performance indicators.

In the next Section, a preliminary description of the proposed approach is briefly presented. The implemented IoT based measurement system is capable to acquire and manage the climate and bioclimate data at farm level and it may use further processing by means of machine learning and artificial intelligence methods to assist livestock farming. According to analysed and surveyed literature, the proposed approach in this paper adopts the MQTT broker to allow for the implemented IoT sensors to send the acquired data to a central communication point. In particular, the Eclipse Mosquitto, which is an open source (EPL/EDL licensed) message broker that implements the MQTT protocol, was adopted. Eclipse Mosquitto is responsible for routing all messages between the sender (i.e., the IoT sensors acting as publishers) and the intended recipient (e.g., a Telegraf agent acting as the subscriber). Next, the Telegraf can process and format the data to make them suitable for InfluxDB (i.e., this is a database that stores time series). InfluxDB provides a simple syntax to perform queries and efficiently add metadata. Finally, Grafana, which is an interactive web application used to easily visualize the data, can present to the final user the data provided by the IoT sensors. Thus, by using an IoT standard framework, such as the one composed by EclipseMosquitto/ Telegraf/InfluxDB/Grafana, ensures that data is properly organized, enhances compatibility between different systems, and allows an easy data evaluation by the end user.

4. PROPOSED APPROACH

The paper aims to propose a methane IoT sensor to be integrated into a livestock farming. The adopted strategy consists in measuring methane concentration produced by Mediterranean buffalo in a real farm environment.

4.1. Enteric CH_4 sensing system

The adopted sensor to measure CH_4 is the Guardian NG [41]. A picture of the sensor is shown in Figure 2, while the main specifications are reported in Table 1

The Guardian range of infrared gas monitors supplied by Edinburgh Sensors offers near-analyser quality continuous sampling, measurement and display of target gas concentrations.

Figure 2 The Guardian NG CH_4 gas measurement system [41].

Table 1. Guardian NG specifications.

Parameter	Value
Range	0 ÷ 5 %
Accuracy	± 2 %
Response Time	T90 ≤ 30 s
Warm-up time	1 minute (initial) 30 minutes (full specifications)
Output	4-20 mA analogue output @ 10 V
Enclosure rating	IP54
Power consumption	13 W typical

The implemented measured technique is based on dual wavelength nondispersive infrared (NDIR) technology.
NDIR is an optical sensing technique where IR radiation interacts with the targeted analyte and it is absorbed depending on the specific absorption spectrum. The sensor performs an indirect concentration measurement based on the Beer-Lambert law [42]:

$$I(\lambda) = I_0(\lambda) \cdot \mathrm{e}^{-\alpha(\lambda) \cdot c \cdot l}\,, \tag{1}$$

where $I(\lambda)$ and $I_0(\lambda)$ are the intensities of detected and emitted radiation, respectively, at a particular wavelength λ and its unit is W/m^2, $\alpha(\lambda)$ is the gas absorption coefficient (product of gas concentration and specific absorptivity of the gas); c is the gas concentration; and l is the path length.

The absorption coefficient $\alpha(\lambda)$ is specific for each gas; in particular, CH_4 exhibits an absorption spectrum centred at 3 μm and 8 μm. The NDIR gas sensor consists of an IR emitter, detector, optical filter, gas chamber, and circuit elements for signal processing. The gas stream throughout the chamber is obtained by a pump ensuring 1 litre per minute flow rate. The presence of the pump slows down the dynamics of the sensor; the response time increases with the increase of the pump tube length, thus requiring to install the sensor near the gas is drawn in. The Guardian range provides high accuracy detection and measurement of CH_4 gas, where detection level ranges between 0÷5 % by volume. The sensor provides reliability, accuracy, long-term stability plus low maintenance requirements, thanks to the proprietary infrared sensor technology. The Guardian is supplied with LCD display and digital alarm set-point controls, housed in a robust plastic IP54 rated enclosure to prevent the ingress of particulates and water.

The Guardian sensor have been preferred to the other sensors based on electrochemical transduction [43]-[44], where the active component is involved in a chemical reaction with the target gas, thus varying a specific physical property (e.g., resistance, refractive index, current density). Electrochemical sensors properly operate in lower concentration ranges (i.e., few tens of ppm), but typically exhibit a drift over the time due to the degradation of the sensible component, thus requiring regular maintenance and frequent calibrations.

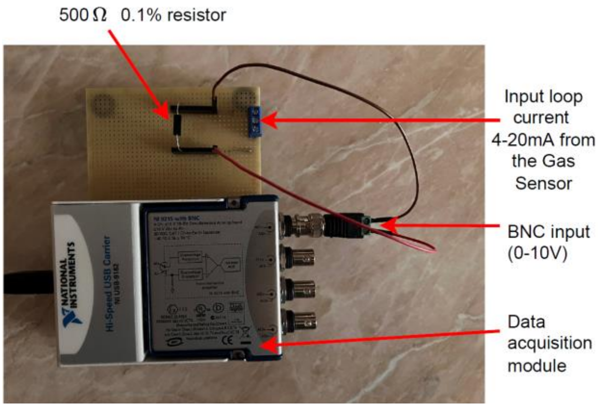

Figure 3. Scheme of the DAQ setup.

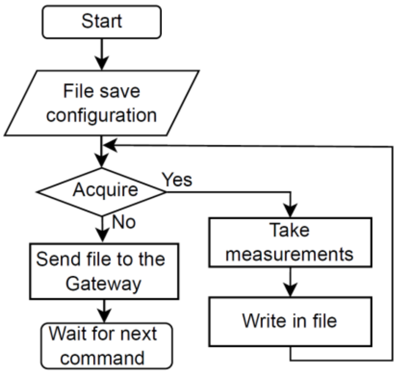

Figure 4. Flowchart example of the LabVIEW executing code.

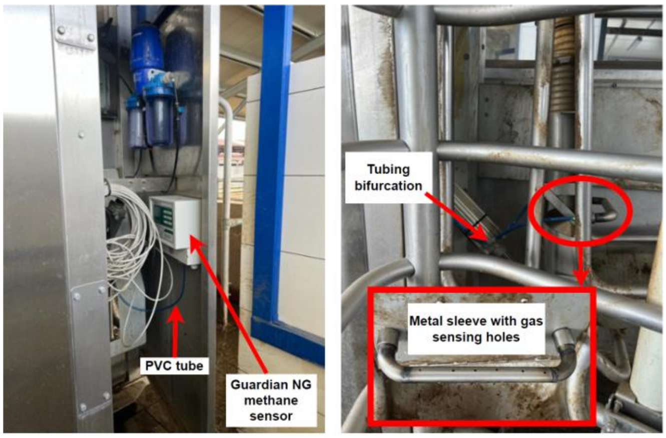

Figure 5. Field placement of the CH_4 gas emission sensing from ruminants.

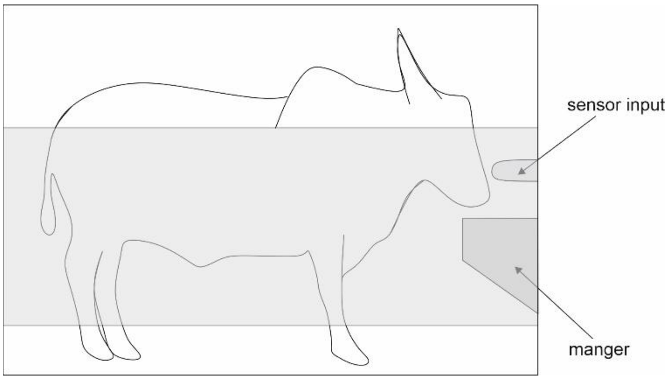

Figure 6. Drawing showing the field placement of the CH_4 gas emission sensor in the milking robot.

4.2. Data acquisition system

The output of the Guardian NG [41] sensor is delivered through a current loop. To this aim, a precision resistance of 500 Ω is used (see Figure 3), where a maximum output voltage of 10V is obtained which corresponds to the maximum sensing range of CH_4. Therefore, in order to acquire the signal delivered by the sensor, being placed at a distance varying from several meters up to several tens of meters, a current loop from the sensor to the workstation was created, using a National Instruments data acquisition card (Figure 3).
An acquisition software was developed in LabVIEW environment which manage the entire acquisition process. The software is therefore divided into two parts: (i) an acquisition part and data saving in file, and (ii) a part managing the data sending in cloud for further processing and decision control. The flowchart of the software architecture is depicted in Figure 4.

First of all, the time stamp is made, to fix the date and time of the acquisition. Then, at the start, the DAQ assistant is configured for the declared time stamp, then the data acquisition card from channel AI0 acquires the desired number of samples, at the desired sample rate in the desired mode, and writes them into file. Once the acquisition process receives a stop request, it sends to the Gateway the file for further elaboration and enters in a wait for next command state. The sampling process through the DAQ assistant from the National Instruments data acquisition card uses a configuration to acquire 10 samples, at a frequency of 50 Hz in continuous mode.

4.3. Field placement and experimental data

In the proposed solution, the methane sensor is installed in the stable, embedded in an automated milking machine (see Figure 5), thus allowing to monitor the gas emission of the buffalo always in the same conditions (i.e., during milking). In particular, when the animal is confined inside the equipment, the pump draws the exhaled gas from small holes realized in a steel tube located just in front of it. To ensure that the buffalo keeps the face close to the tube and to favour gas belching, a small manger has been placed just below the tube and provided with a highly appealing feed, as shown in Figure 6.

The milking machine identifies the animal by means of an RFID system.

In Figure 7 the behaviour of the CH_4 concentration over the whole day is reported. It exhibits a peculiar shape dominated by peaks occurring as a buffalo approaching the sensor input (i.e., the buffalo in the milking robot close). The amplitude of peaks ranges in the interval of 0-4500 ppm.

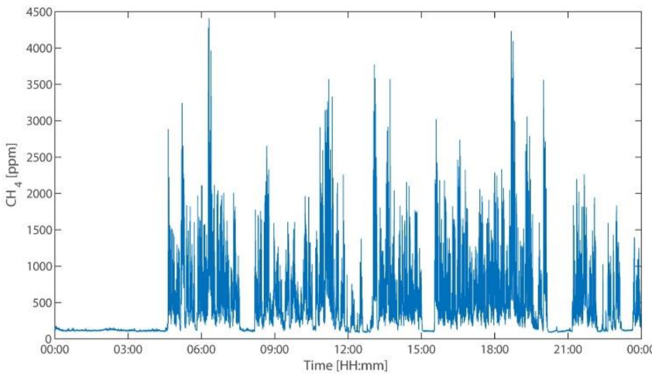

Figure 7. Measurement of CH_4 concentration over a day.

Thanks to a suitable response time, the sensor properly senses the emitted gas concentration even in the reduced time windows when the buffalo assumes the right position, while providing the background values when the milking robot is empty.

It should be remarked that the emission value can be obtained by integrating the gas concentration over the time windows the milking machine associate to the specific buffalo, but subtracted by the base value, determined as the initial concentration value in the same time period.

4.4. Advantages and drawbacks of the proposed approach

The proposed technique provides the following advantages:

- it ensures an accurate measure of instantaneous methane concentration;
- it allows to monitor the methane emissions in specific animal condition (i.e., just before milking);
- it is able to associate the measures to an individual cattle thanks to RFID technology;
- it is suitable to be integrated in real farms; as an example, the proposed sensor is successfully integrated in a milking machine;
- it does not impact on animal welfare.

Nevertheless, the following critical aspects have yet to be addressed:

- methane gas emission is evaluated far from the rumination phase, thus limiting the amount of gas the buffalo produces during the measure;
- since the stable is an open system, the instantaneous concentration of CH_4 can be related to the emissions only if it is assumed that the entire expired gas is drawn by the pump and the measure is not affected by any other emission contribution.

5. CONCLUSIONS

In this paper, the recent advances in sensors technologies and their IoT-based measurement systems adopted for enteric methane emission monitoring in ruminants was presented.

Moreover, a methane concentration measurement system to be installed in real buffalo livestock farm was presented and the choice of its components discussed.

The system, integrated in a milking machine, is designed to periodically monitor the emission of individual buffalos in specific conditions (i.e., during milking) without significantly affecting the animal welfare.

Future work is directed to investigate a robust technique to relate isolated measurements of methane instantaneous concentration to the amount of gas emission of a buffalo during the whole day.

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REFERENCES

[1] IPCC, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2021. Online [Accessed 26 November 2023].
https://www.ipcc.ch/report/ar6/wg1/

[2] International Energy Agency, IEA (2021), World Energy Outlook 2021, IEA, Paris, License: CC BY 4.0. Online [Accessed 26 November 2023].
https://www.iea.org/reports/world-energy-outlook-2021

[3] D. Moran, E. Wall, Livestock production and greenhouse gas emissions: Defining the problem and specifying solutions, Animal Frontiers 1(1) (2011), pp. 19-25.
DOI: 10.2527/af.2011-0012

[4] W. Bekele, A. Guinguina, A. Zegeye, A. Simachew, M. Ramin, Contemporary methods of measuring and estimating methane emission from ruminants, Methane 1(2) (2022), pp. 82-95.
DOI: 10.3390/methane1020008

[5] V. Palangi, A. Taghizadeh, S. Abachi, M. Lackner, Strategies to mitigate enteric methane emissions in ruminants: A review, Sustainability 14(20) (2022).
DOI: 2071-1050/14/20/13229

[6] J. Knapp, G. Laur, P. Vadas, W. Weiss, J. Tricarico, Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions, Journal of Dairy Science 97(6) (2014), pp. 3231-3261.
DOI: 10.3168/jds.2013-7234

[7] E. Balestrieri, L. De Vito, F. Lamonaca, F. Picariello, S. Rapuano, I. Tudosa, Research challenges in measurements for internet of things systems, Acta IMEKO 7(4) (2018), pp. 82-94.
DOI: 10.21014/acta_imeko.v7i4.675

[8] P. Daponte, F. Lamonaca, F. Picariello, L. De Vito, G. Mazzilli, I. Tudosa., A Survey of Measurement Applications Based on IoT, Proc. of IEEE Int. Workshop on Metrology for Industry 4.0 and IoT, Brescia, Italy, 16-18 April 2018, pp. 1-6.
DOI: 10.1109/METROI4.2018.8428335

[9] C. Scuro, F. Lamonaca, S. Porzio, G. Milani, R. S. Olivito, Internet of Things (IoT) for masonry structural health monitoring (SHM): Overview and examples of innovative systems, Construction and Building Materials 290 (2021), pp. 1-17.
DOI: 10.1016/j.conbuildmat.2021.123092

[10] A. Liccardo, F. Bonavolontà, R. Schiano Lo Moriello, F. Lamonaca, L. De Vito, A. Gloria, E. Caputo, G. de Alteriis, Digital twins based on augmented reality of measurement instruments for the implementation of a cyber-physical system, Acta IMEKO 11(4) (2022), pp. 1-8.
DOI: 10.21014/actaimeko.v11i4.1397

[11] F. Lamonaca, D. L. Carnì, Evaluation of the effects of mobile smart object to boost IoT network synchronization, Sensors 21(12) (2021), pp. 1-14.
DOI: 10.3390/s21123957

[12] I. Tudosa, F. Picariello, E. Balestrieri, L. De Vito, F. Lamonaca, Hardware Security in IoT era: the Role of Measurements and Instrumentation, proc. of IEEE Int. Workshop on Metrology for Industry 4.0 and IoT, Naples, Italy, 4-6 June 2019, pp.285-290.
DOI: 10.1109/METROI4.2019.8792895

[13] A. Bria, G. Cerro, M. Ferdinandi, C. Marrocco, M. Molinara, An IoT-ready solution for automated recognition of water contaminants, Pattern Recognition Letters 135 (July 2020), pp. 188-195.
DOI: 10.1016/j.patrec.2020.04.019

[14] L. Angrisani, A. Amodio, P. Arpaia, M. Asciolla, A. Bellizzi, F. Bonavolontà, R. Carbone, E. Caputo, G. Karamanolis, V. Martire et al., An innovative air quality monitoring system based on drone and IoT enabling technologies, in 2019 IEEE Int. Workshop on Metrology for Agriculture and Forestry (MetroAgriFor), Portici, Italy, IEEE, 24-26 October 2019, pp. 207-211.
DOI: 10.1109/MetroAgriFor.2019.8909245

[15] M. Carratú, V. Gallo, V. Paciello, IEEE 1451: Communication among smart sensors using MQTT protocol, 2022 IEEE Int. Symp. on Measurements & Networking (M&N), Padua, Italy, 18-20 July 2022, pp. 1-6.
DOI: 10.1109/MN55117.2022.9887708

[16] V. Palco, G. Fulco, C. De Capua, F. Ruffa, M. Lugarà, IoT and IAQ monitoring systems for healthiness of dwelling, 2022 IEEE

Int. Workshop on Metrology for Living Environment (MetroLivEn), Cosenza, Italy, 25-27 May 2022, pp. 105-109.
DOI: 10.1109/MetroLivEnv54405.2022.9826946

[17] T. Aldhafeeri, M.-K. Tran, R. Vrolyk, M. Pope, M. Fowler, A review of methane gas detection sensors: Recent developments and future perspectives, Inventions 5(3) (2020).
DOI: 10.3390/inventions5030028

[18] Zeba Idrees, Lirong Zheng, Low cost air pollution monitoring systems: A review of protocols and enabling technologies, Journal of Industrial Information Integration, vol. 17, March 2020, 100123.
DOI: 10.1016/j.jii.2019.100123

[19] M. Chagunda, Opportunities and challenges in the use of the laser methane detector to monitor enteric methane emissions from ruminants, Animal 7 (2013), pp. 394-400.
DOI: 10.1017/S1751731113000724

[20] J. Hill, C. McSweeney, A.-D. G. Wright, G. Bishop-Hurley, K. Kalantar-zadeh, Measuring methane production from ruminants, Trends in Biotechnology 34(1) (2016), pp. 26-35.
DOI: 10.1016/j.tibtech.2015.10.004

[21] C. Knight, Review: Sensor techniques in ruminants: more than fitness trackers, Animal 14 (2020), pp. s187-s195.
DOI: 10.1017/S1751731119003276

[22] V. Smil, Planet of the cows [numbers don't lie], IEEE Spectrum 54(4) (2017), p. 24.
DOI: 10.1109/MSPEC.2017.7880453

[23] M. Alipio, M. L. Villena, Intelligent wearable devices and biosensors for monitoring cattle health conditions: A review and classification, Smart Health 27 (2023), p. 100369.
DOI: 10.1016/j.smhl.2022.100369

[24] L. Martínez Rau, J. O. Chelotti, S. R. Vanrell, L. L. Giovanini, Developments on real-time monitoring of grazing cattle feeding behavior using sound, 2020 IEEE Int. Conf. on Industrial Technology (ICIT), Buenos Aires, Argentina, 26-28 February 2020, pp. 771-776.
DOI: 10.1109/ICIT45562.2020.9067192

[25] H. Wu, F. Bai, Z. Zhong, X. Cheng, D. Fan, Research on cow rumination monitoring based on new activity sensor, 2019 9th International Conference on Information Science and Technology (ICIST), Hulunbuir, China, 2-5 August 2019, pp. 199–204.
DOI: 10.1109/ICIST.2019.8836709

[26] L. Cruz-Rivero, N. F. Mateo-Díaz, R. Purroy-Vásquez, D. Angeles-Herrera, F. Osorio-Cruz, Statistical analysis for a non-invasive methane gas and carbon dioxide measurer for ruminants, in 2020 IEEE International Conference on Engineering Veracruz (ICEV), Boca del Rio, Mexico, 26-29 October 2020, pp. 1-7.
DOI: 10.1109/ICEV50249.2020.9289668

[27] L. Cruz-Rivero, M. L. Méndez-Hernández, C. E. Mar-Orozco, A. A. Aguilar-Lasserre, A. Barbosa-Moreno, J. Sánchez-Escobar, Functional evaluation using fuzzy fmea for a non-invasive measurer for methane and carbone dioxide, Symmetry 14(2) (2022), art. No. 421.
DOI: 10.3390/sym14020421

[28] H. Zheng, H. Wang, T. Yan, Modelling enteric methane emissions from milking dairy cows with Bayesian networks, 2016 IEEE Int. Conf. on Bioinformatics and Biomedicine (BIBM), Shenzhen, China, 15-18 December 2016, pp. 1635-1640.
DOI: 10.1109/BIBM.2016.7822764

[29] A. N. Hristov, J. Oh, F. Giallongo, T. Frederick, H. Weeks, P. R. Zimmerman, M. T. Harper, R. A. Hristova, R. S. Zimmerman, A. F. Branco, The use of an automated system (greenfeed) to monitor enteric methane and carbon dioxide emissions from ruminant animals, JoVE Journal 103(e52904) (2015).
DOI: 10.3791/52904

[30] C. De Capua, A. Liccardo, R. Morello, On the web service-based remote didactical laboratory: further developments and improvements, Proc. of the 2005 IEEE Instrumentation and Measurement Technology Conf., Ottawa, ON, Canada, 16-19 May 2005, pp. 1692-1696.
DOI: 10.1109/IMTC.2005.1604458

[31] A. Baccigalupi, C. De Capua, A. Liccardo, Overview on development of remote teaching laboratories: from Labview to web services, Proc. of the 2006 IEEE Instrumentation and Measurement Technology Conf., Sorrento, Italy, 24-27 April 2006, pp. 992-997.
DOI: 10.1109/IMTC.2006.328272

[32] G. de Alteriis, C. Conte, E. Caputo, P. Chiariotti, D. Accardo, A. Cigada, R. Schiano Lo Moriello, Low-cost and high-performance solution for positioning and monitoring of large structures, Sensors 22(5) (2022), art. No. 1788.
DOI: 10.3390/s22051788

[33] F. Lamonaca, C. Scuro, D. Grimaldi, R. Sante Olivito, F. P. Sciammarella, D. L. Carnì, A layered IoT-based architecture for a distributed structural health monitoring system, Acta IMEKO 8(2), pp. 45-52.
DOI: 10.21014/acta_imeko.v8i2.640

[34] F. Lamonaca, P. F. Sciammarella, C. Scuro, D. L. Carnì, R. S. Olivito, Synchronization of IoT Layers for Structural Health Monitoring, Proc. of Workshop on Metrology for Industry 4.0 and IoT, MetroInd 4.0 and IoT, Brescia, 16-18 April 2018, pp. 89-94.
DOI: 10.1109/METROI4.2018.8428329

[35] W. Kim, W. Lee, Y. Kim, A review of the applications of the internet of things (IoT) for agricultural automation, Journal of Biosystems Engineering 45 (2020), pp. 385-400.
DOI: 10.1007/s42853-020-00078-3

[36] B. I. Akhigbe, K. Munir, O. Akinade, L. Akanbi, L. O. Oyedele, IoT technologies for livestock management: A review of present status, opportunities, and future trends, Big Data and Cognitive Computing 5(1) (2021).
DOI: 10.3390/bdcc5010010

[37] P. Daponte, L. De Vito, G. Mazzilli, S. Rapuano, I. Tudosa, Network design and characterization of a wireless active guardrail system, 2014 IEEE Int. Instrumentation and Measurement Technology Conf. (I2MTC), Montevideo, Uruguay, 12-15 May 2014, pp. 1047-1052.
DOI: 10.1109/I2MTC.2014.6860902

[38] I. Tudosa, F. Picariello, E. Balestrieri, D. L. Carnì, F. Lamonaca, A Flexible DAQ Hardware Architecture using SoCs for IoT based Structural Health Monitoring Systems, Proc. of IEEE Int. Workshop on Metrology for Industry 4.0 and IoT, MetroInd 4.0 and IoT, 2019, pp. 291-295.
DOI: 10.1109/METROI4.2019.8792900

[39] P. Daponte, L. De Vito, F. Italiano, G. Lazzaro, F. Picariello, S. S. Scappuzzo, I. Tudosa, Flexible battery-powered data acquisition system for sub-marine monitoring, Proc. of IEEE Int. Workshop on Metrology for the Sea, Milazzo, Italy, 3-5 October 2022, pp. 158–163.
DOI: 10.1109/MetroSea55331.2022.9950741

[40] L. Angrisani, F. Bonavolontà, A. Tocchi, R. S. L. Moriello, Frequency domain measurement node based on compressive sampling for sensors networks, 2015 IEEE Int. Workshop on Measurements & Networking (M&N), Coimbra, Portugal, 12-13 October 2015, pp. 1-5.
DOI: 10.1109/IWMN.2015.7322972

[41] Edinburgh Instruments Ltd., Guardian ng - infrared gas monitor - user guide. Online [Accessed 26 November 2023]
http://www.edinburghsensors.com

[42] G. Patrizi, A. Bartolini, L. Ciani, V. Gallo, P. Sommella, M. Carratù, A virtual soil moisture sensor for smart farming using deep learning, IEEE Transactions on Instrumentation and Measurement 71 (2022).
DOI: 10.1109/TIM.2022.3196446

[43] R. K. Jha, Non-dispersive infrared gas sensing technology: A review, IEEE Sensors Journal 22(1) (2022), pp. 6-15
DOI: 10.1109/JSEN.2021.3130034

[44] P. K. Sekhar, J. Kysar, E. L. Brosha, C. R. Kreller, Development and testing of an electrochemical methane sensor, Sensors and Actuators B: Chemical 228 (2016), pp. 162-167.
DOI: 10.1149/MA2016-01/39/1953