A SMART SYSTEM FOR DAIRY COW LOCALIZATION IN CUBICLES BASED ON ULTRASONIC SENSING AND MACHINE LEARNING

Vladimír MADOLA [1], Lukáš VACHO [2], Vladimír CVIKLOVIČ [2], Jana LENDELOVÁ [3], Peter HLAVÁČ [2], Miroslav HOLÝ [2]

[1] Information and Coordination Centre of Research, Faculty of Engineering, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2, SK-94976 Nitra, Slovakia.
[2] Institute of Electrical Engineering, Automation, Informatics and Physics, Faculty of Engineering, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2, SK-94976 Nitra, Slovakia.
[3] Institute of Agricultural Engineering, Transport and Bioenergetics, Faculty of Engineering, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2, SK-94976 Nitra, Slovakia.

Abstract
The paper deals with the implementation of machine learning classification algorithms for determining the position of a dairy cow in a cubicle via ultrasonic distance measurement. A unique measurement system has been developed to monitor the welfare of dairy cows via analysis of their activity in cubicle. The position of the dairy cow was considered against the measurement system as axial and radial position in the cubicle. As the best accurate classification model was recognized Random Forest with an accuracy value of 0.92. From the unsupervised models, Label Propagation had the best fit with an accuracy value of 0.88 and an ARI value of 0.557. The results have demonstrated that the important value in ultrasound position determination are the measured distance and the ultrasound signal amplitude. The proposed ultrasonic-based method offers a non-contact alternative to collar-mounted and image-analysis systems for practical dairy cow welfare monitoring.
Key words: *animal detection; animal welfare; cattle; machine learning; smart farming; ultrasound.*

INTRODUCTION
Smart farming denotes that future farms will require the integration of advanced information technologies to achieve greater profitability, efficiency, safety, and environmental sustainability. In dairy farming, this involves collecting both direct and indirect information, as well as analysing welfare assessment protocols *(Fraser, 2018)*. The conditions under which dairy cows rest and lie are particularly significant when viewed through the perspective of the convergence of competitive animal production and animal welfare. Current commercial systems for recording animal activity are based on varying functional principles *(Idris et al., 2023)*. The following factors have been identified as being relevant to the study: the lying behaviour of dairy cows, both in terms of position *(in cubicles or corridors)* and number of legs in contact with the cubicle floor *(i.e. whether the cow is standing, sitting or lying down)*; and the effect of stocking density on duration of lying in each cubicle. It is important to understand that these characteristics are key elements in the study of animal response to the quality of the breeding environment *(Krawczel & Lee, 2019)*. In practice, the use of automated commercial systems by farmers involves drawbacks such as significant upfront costs, the complexity involved in accessing the final data, and the varied pros and cons of sensors that are either connected or not *(Fan et al., 2022)*. Employing an ultrasonic system to pinpoint the location of a dairy cow within a cubicle is advantageous owing to its affordability, straightforwardness, and robustness against electromagnetic and light interference, as well as pollution and weather conditions. Ultrasound signal combined with machine learning algorithms was used in our research to monitor the position of animal in cubicles. The potential is in the various applications for smart agriculture, in the research tasks of scientists, but also in authors' own innovative inspirations and needs for improvement, in cases of monitoring and evaluation experiments exploring resting areas. Existing automated systems for variable measurement and data classification include several function blocks at the base, such as pre-processing, feature extraction, and classification system. Modifications *(Thang et al., 2018)* of SVM classification methods achieve results with high accuracy and sensitivity *(Bhaskar, 2015)*, where the SVM classification algorithm has potential applications in technical systems used in identifying the position of dairy cow in a defined area using multiple sensors. The aim of this research is to study the problem of the accuracy of monitoring the position

of animals in a defined area of a cubicle, where an ultrasound measurement system with selected classification algorithms was used. A unique measurement system has been developed.

MATERIALS AND METHODS

Measuring condition for cubicle and used measurement system

The experiments were realized on a university farm in the south-west of Slovakia *(a large-capacity dairy farm with Holstein-Friesian)*, where the defined area was represented as a single box with plan dimensions: 1.25 m × 2.50 m *(Fig. 1A)*. The experiments were performed without any disturbance to the breeding animals.

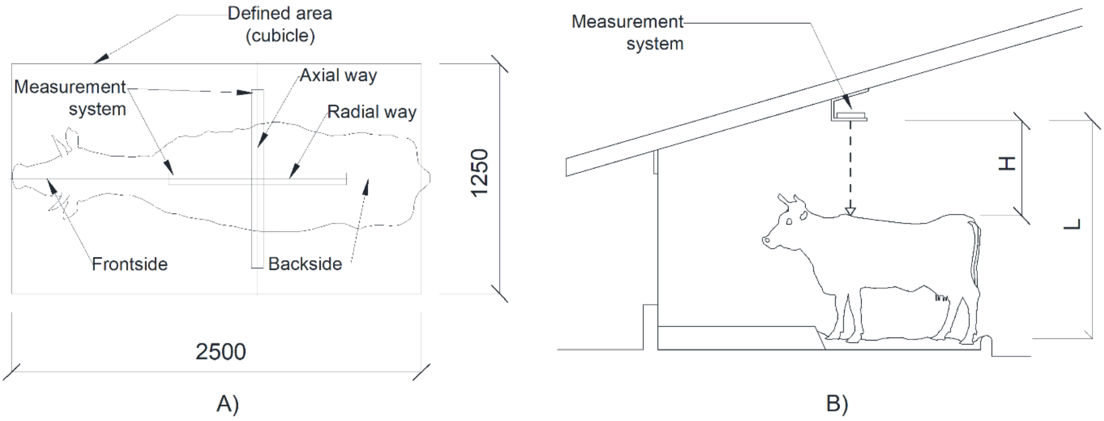

Fig. 1 Principal representation of experimental conditions; A – Principal illustration of measurements in cubicle occupied by an animal in experiment *(dimensions are in mm)*; B – animal presence and implemented measurement system in cubicle.

The modification of the original design of the measuring system *(Lendelová et al., 2014)* achieved the sectorization of the cubicle area. The sensors were arranged in an array of five SensComp 40LR16 sensors, which acquire ultrasonic reflections from the back of a dairy cow. The configuration of the ultrasonic transducers in the experiment is defined by a parabola with specified dimensions. The transducers at positions R2, R3, R4 and R5 are considered as receivers and the transducer R1 as a transmitter and receiver. The detailed overview of the ultrasound sensor layout is presented in the paper *(Madola et al., 2023)*. The height from the base refers to the position of sensor R1, which is in the axis of the measurement system, where the given axis intersects the sensor and is perpendicular to the base.

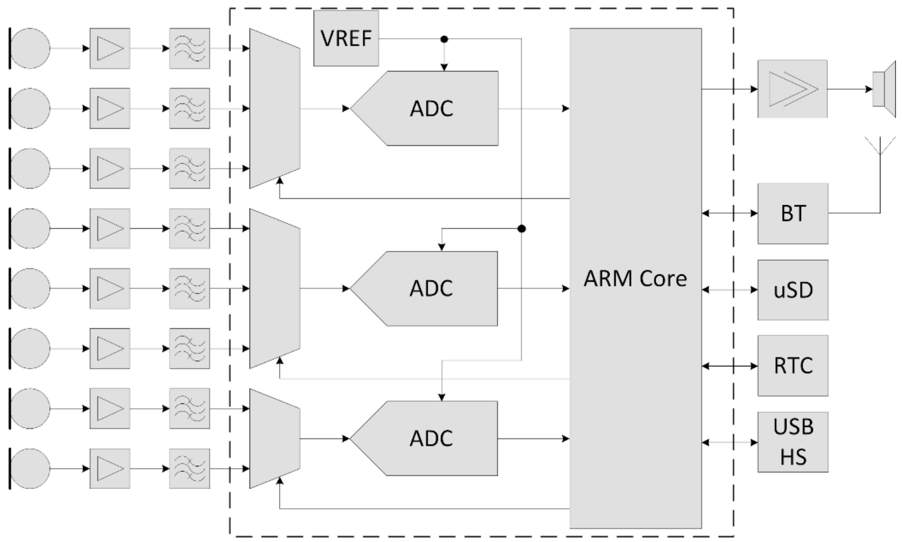

Fig. 2 The block diagram illustrates the experimental device.

The resonance frequency of the transmitter and receiver is identical, at 40 kHz ± 1 kHz which is the frequency higher than the hearing limit of cattle *(Brouček, 2014)*. The directional angle of the ultrasonic transducers is a range of ±27.5° for -6 dB attenuation. The signal from the transducers is amplified by a two-stage amplifier in an inverting circuit and then filtered by a second-order high-pass filter. For this reason, the signal sampling rate was set to 250 kHz. The Analog to Digital converters *(ADC)* and multiplexers are used integrated in the STM32H7A3ZI microcontroller. The transfer of measured data from AD converters to memory uses DMA *(Direct Memory Access)* principle. The ultrasound output signal is generated by a Digital to Analog converter *(DA)* with the possibility to adjust the number of transmitted waves and the transmission period. A block diagram of the experimental apparatus is shown in Fig. 2. The data is saved on a uSD memory card. The High-Speed USB *(USB HS)* is also available.

Characteristics of position model and processing of experimental data

The experiment was evaluated using selected characteristics of the ultrasound signal, such as the amplitude of the ultrasound signal reflected from the cow in a defined area and measured distance by impulse method via ultrasound. For the model of the position of the dairy cow in the defined area with respect to the measurement system *(Radial and Axial position)*, a Linear SVM, K-Means, KNN, Label Propagation and Random Forest classifiers were used. In each dairy cow position, the measurement was performed with 10 repetitions. The measured dataset of distances and amplitudes for the radial and axial position data instances were separated into training and test sequences in a 70:30 ratio. The validation of the classifier position machine learning methods was performed on the data for the case of a standing dairy cow in the defined area. The experiment was conducted at two vertical levels away from the dairy cow *(Fig. 1B)*: L1 as the low-height case *(H1 value of 1.07 m ± 0.0361 m)* and L2 as the high-height case *(H2 value of 1.22 m ± 0.0304 m)*. Data randomization was applied to each dataset for repeatability. For the Label propagation classifier, the KNN kernel was used, and the number of neighbours was set to 5. The robustness of the classification models was evaluated by Accuracy, Precision, Recall, Weighted F1 score *(F1)*, Matthews Correlation Coefficient *(MCC)*, Adjusted Rand Index *(ARI)* and Normalized Mutual Information *(NMI)*. These metrics, which express model robustness, are dimensionless. The analysis of experimental data and the creation of classification models were performed under Python 3.12.3.

RESULTS AND DISCUSSION

Statistical analysis of measured signal amplitudes and distances

Through changing the measurement height from L1 to L2, statistically significant differences between the measured heights at each sensor were identified *($p \leq 0.0001$)*. The coefficient of variation did not exceed 2.50%. Agreement with the normal probability distribution *($p > 0.05$)* of the lengths measured by the impulse ultrasound method was confirmed. The amplitude of the ultrasound signals in selected measurements exceeded the value of relative variability by over 50%. Statistical analysis of the signal amplitudes measured across the individual sensors indicated no statistically significant differences. A detailed comparison of the amplitude values by nested one-way ANOVA is presented in Tab. 1.

Tab. 1 Statistical evaluation of signal amplitude differences in various dairy cow positions

Position	p-value
Axial position at L1 vs. Radial position at L1	0.12
Axial position at L1 vs. Axial position at L2	0.60
Axial position at L1 vs. Radial position at L2	0.79
Radial position at L1 vs. Axial position at L2	0.69
Radial position at L1 vs. Radial position at L2	0.50
Axial position at L2 vs. Radial position at L2	0.99

Agreement with the log-normal probability distribution of ultrasound signal amplitudes was confirmed *($p > 0.05$)*. The statistical representation of the measured ultrasound signal amplitudes *(Mean ± 95% Confidence interval)* is depicted in Fig. 3. In view of the statistically insignificant differences for the ultrasound signal amplitudes, we could not determine by descriptive statistics the categorization of the individual dairy cow positions. Based upon the statistics, the data were analysed by the selected machine learning classification models. The classification model datasets will only contain the amplitudes of the ultrasonic signal on individual sensors.

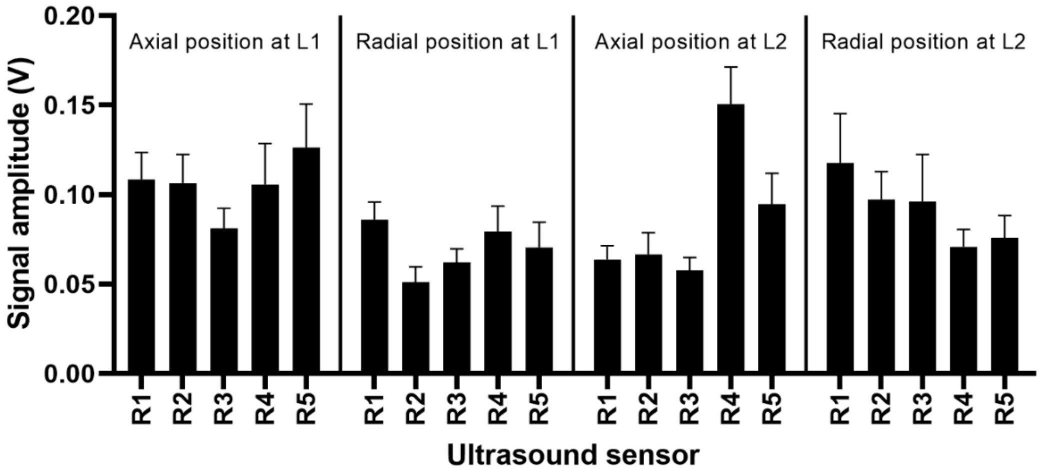

Fig. 3 Statistical evaluation of measured ultrasound signal amplitudes.

The results of the selected models are summarized in the following section, where using the metrics of the models, from the analysis indicates the specifics of the individual classification parameters under testing.

Evaluation of dairy cow positions classification models

By classifying the position of the dairy cow in the specified zone with machine learning models, the Random Forest model achieved the best results in the view of correlation *(MCC value of 0.83)* from the group of supported models. The best accuracy rate was achieved by the Random Forest classifier *(Accuracy value of 0.92)*. Concerning the unsupervised classification models, the most suitable model was found Label Propagation *(ARI value of 0.56)*. The ARI metrics value confirms that the models are resistant from cross misclassification independent of labelled data. A detailed evaluation of the classification model metrics is presented by radar plot in Fig. 4.

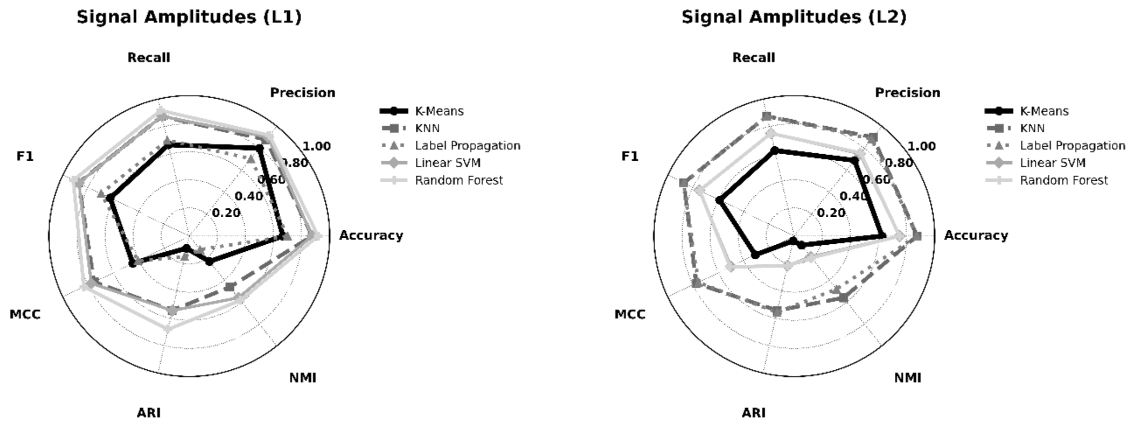

Fig. 4 Radar plot of classification model metrics for dairy cow position.

The most unsatisfactory classification results regarding individual dairy cow positions were achieved by the K-Means model, where 67% of axial positions were incorrectly determined as radial *(at L1* *height)* and 67% of radial positions were incorrectly determined as axial *(at L2 height)*. The confusion matrices of the selected classification models are depicted in Fig. 5.

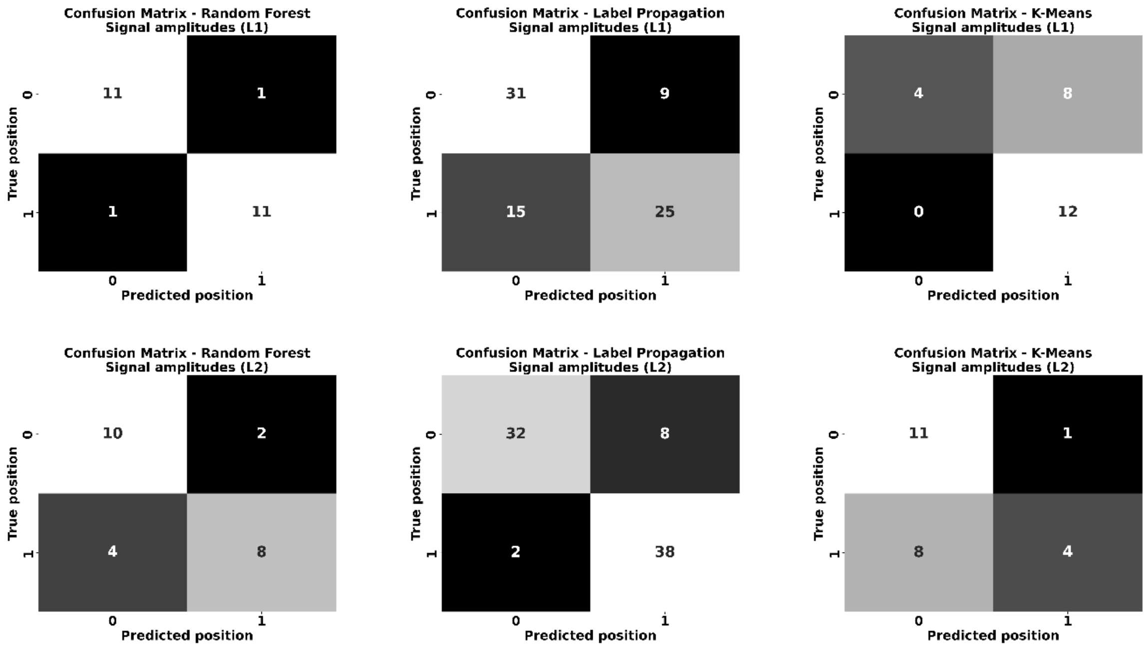

Fig. 5 Confusion matrices of selected dairy cow position classification models on verification *(0 – Axial position of dairy cow; 1- Radial position of dairy cow)*.

The study of the environment of animals in the context of welfare is one of the important aspects in relation to the factors that affect the behaviour of the animals in the barn environment itself *(Tucker et al., 2020)*. Providing adequate welfare conditions for dairy cows requires monitoring of physical activity as well as positioning within the cubicle. In principle, different measuring systems *(Hrubý et al., 2022; Ayrulu & Barshan, 2001)* and machine learning methods *(Wang et al., 2024; Karagoz & Dindis, 2025)* can be used for data processing. In comparison, a method based on the ultrasonic principle provides reliable results with respect to the surrounding environment conditions.

CONCLUSIONS

The contribution was focused on the classification of dairy cow position in cubicle by applying machine learning using ultrasonic distance measurement method. It is obvious from the results that it is not possible to use standard forms of regression to determine the position of a dairy cow based on the processing of the ultrasound signal. The coefficient of variation of the ultrasound signal amplitudes exceeded 50% in several measurements. Unsupervised and supervised classification models were selected. The most predictive model was shown to be Random Forest, where the accuracy value reached value of 0.92. From the unsupervised models, Label Propagation is the most superior, where the accuracy value reached value up to 0.88. Simultaneously, the ARI values were evaluated, where the unsupervised classifiers performed the best models *(Label propagation; ARI value 0.56)*. A universal method for position classification was determined. It was demonstrated that the distance measured by the ultrasound method, together with the individual values of the signal amplitudes, has an informative value in determining the position of a dairy cow in the cubicle. The findings will support the analysis of dairy cow welfare in the implementation of non-conventional intelligent systems in dairy farming as smart farming. The proposed approach represents a low-cost system suitable for practical welfare monitoring. It also provides an alternative to commercial solutions based on image analysis, GPS systems, or neck-mounted collar sensors. Future research will focus on full-scale ultrasonic signal processing with machine learning for improved cow position classification. It is also considered for future implementation on dairy cow farms to enlarge the dataset.

ACKNOWLEDGMENT

This contribution was supported by Project No. 09I03-03-V04-00485 Identification of housed animals' activity by ultrasound. Investment No. 3. Excellent Science, funded by the European Union from the Recovery and Resilience Plan of the Slovak Republic.

REFERENCES

1. Ayrulu, B., & Barshan, B. *(2001)*. Neural networks for improved target differentiation and localization with sonar. Neural Networks, 14*(3)*, 355–373.
2. Bhaskar, N. A. *(2015)*. Performance Analysis of Support Vector Machine and Neural Networks in Detection of Myocardial Infarction. Procedia Computer Science, 46, 20–30.
3. Brouček, J. *(2014)*. Effect of noise on performance, stress, and behaviour of animals. Slovak journal of animal science, 47*(2)*, 111-123.
4. Fan, B., Bryant, R., & Greer, A. *(2022)*. Behavioral Fingerprinting: Acceleration Sensors for Identifying Changes in Livestock Health. J. 5*(4)*, 435–454.
5. Fraser, D. *(2018)*. Animal welfare: Translating science into practice. In Advances in Agricultural Animal Welfare: Science and Practice. J. A. Mench, ed. Woodhead Publishing, Duxford, UK.
6. Hrubý, D., Vacho, L., Kubík, Ľ., Tóth, L., Baláži, J., Kósa, P., & Kišev, M. *(2022)*. Characteristics of distance errors of infrared sensor relation to colour surfaces. Acta Technologica Agriculturae, 25*(1)*, 40–46.
7. Idris, M., Gay, C. C., Woods, I. G., Sullivan, M. J., Gaughan, J. B., & Phillips, C. J. C. *(2023)*. Automated Quantification of the Behaviour of Beef Cattle Exposed to Heat Load Conditions. Animals, 13*(6)*, 1125–1125.
8. Karagoz, A., & Dindis, G. *(2025)*. Object Recognition and Positioning with Neural Networks: Single Ultrasonic Sensor Scanning Approach. Sensors, 25*(4)*, 1086.
9. Krawczel, P. D., & Lee, A. R. *(2019)*. Lying Time and Its Importance to the Dairy Cow: Impact of Stocking Density and Time Budget Stresses. Veterinary Clinics of North America: Food Animal Practice, 35*(1)*, 47–60.
10. Lendelová, J., Cviklovič, V., Olejár, M., & Pogran, Š. *(2014)*. Recording system and method of positional identification of animals *(Patent SK1322013U1)*.
11. Madola, V., Cviklovič, V., & Rokosz, K. *(2023)*. Modelling of Impulse Functions of Ultrasonic Sensors When Tilt Angle of Reflecting Surface is Changed. Acta Technologica Agriculturae, 26*(1)*, 1–8.
12. Thang, P. Q., Thuy, N. T., & Lam, H. T., *(2018)*. A Modification of Solution Optimization in Support Vector Machine Simplification for Classification. Information Systems Design and Intelligent Applications, 149–158.
13. Tucker, C. B., Jensen, M. B., De Passillé, A. M., Hänninen, L., & Rushen, J. *(2020)*. Invited review: Lying time and the welfare of dairy cows. Journal of Dairy Science, 104*(1)*, 20–46.
14. Wang, R., Li, Y., Yue, P., Yuan, C., Tian, F., & Lu, X. *(2024)*. Advanced dairy cow monitoring: enhanced detection with precision 3D tracking. Multimedia Tools and Applications.

Corresponding author:

Ing. Lukáš Vacho, Ph.D., Institute of Electrical Engineering, Automation, Informatics and Physics, Faculty of Engineering, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2, SK-94976 Nitra, Slovakia, phone: +421 37 641 4763, e-mail: lukas.vacho@uniag.sk