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FACULTY OF MATHEMATICS AND INFORMATICS
DEPARTMENT OF COMPUTER SYSTEMS

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IoT ENVIRONMENT FOR INTELLIGENT LIVESTOCK

ABSTRACT
On
DISSERTATION THESIS
FOR AWARDING THE EDUCATIONAL AND SCIENTIFIC DEGREE OF **"DOCTOR"**
Field of higher education 4. Natural sciences, mathematics and computer science
Professional field 4.6. Informatics and computer science
Doctoral Program "Informatics" at the Department of "Computer Systems"

Scientific supervisors: Prof. Dr. Stanimir Stoyanov
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Plovdiv 2025.

The dissertation work was discussed and directed for defense by the department council of the Department of Computer Informatics of the Faculty of Mathematics and Informatics at the Paisii Hilendarski University of Plovdiv on February 14, 2025.

The dissertation contains 133 pages. The bibliography includes 111 sources. The number of author's publications on the topic of the dissertation is 2.

The defense of the dissertation will take place on ……………… at ………… in the Conference Hall, New Building of Plovdiv University, 236 Bulgaria Blvd.

The materials for the defense are available to those interested in the Dean's Office of the Faculty of Philosophy - room 330 in the New Building of the "Paisiy Hilendarski" University, every working day from 8:30 to 17:00.

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Plovdiv, 2025

CONTENTS

INTRODUCTION

Modern digital technologies and the application of algorithms and models from artificial intelligence provide increasingly broad opportunities for data processing in a dynamically changing environment, as well as the provision of appropriate services for users in all areas of our lives. Agriculture is becoming an increasingly relevant area of research in the field of IoT (Internet of Things). Modeling and prototyping of intelligent systems in the field of animal husbandry provide an appropriate environment for optimizing production processes in the phase of preliminary development of these systems. In our country, the Concept for Digital Transformation of the Bulgarian Industry of the Ministry of Economy of the Republic of Bulgaria defines as a key necessity the improvement of the quality of agricultural products through the use of intelligent systems that support the management of technological processes through the possibility of automated monitoring, data collection and the application of appropriate algorithms for analysis. The National Scientific Program for Smart Agriculture in Bulgaria, in its part for smart livestock breeding, sets as its main task the use of IoT for monitoring the environment, health, development, behavior and reproduction of cattle, in connection with the modeling of biologically appropriate breeding technologies.

In accordance with the main directions in the development of the digital society and the basic strategies, guidelines and regulatory documents, the main goals and objectives of this dissertation research have been determined.

Main goal:

Exploring the possibilities and building an IoT-based cyber-physical platform for smart livestock farming.

To achieve this goal, the following several main tasks have been defined:

Main tasks of the dissertation research:

- ✓ *To explore the need and possibilities for building an IoT ecosystem in the field of smart livestock farming;*
- ✓ *To develop appropriate software architecture for the platform;*
- ✓ *To create a prototype of a software and hardware IoT platform for smart pasture cattle farming*
- ✓ *To propose an approach for processing and analyzing the obtained data to study the behavior of cows during pasture farming in the created prototype.*

The methodology of scientific research is based on a step-by-step iterative approach, which goes through: familiarization with the problem; design and development of various approaches and models; prototyping; testing and conclusions. In the course of the work, various prototypes were designed, created and tested in the construction of the sensor network and sensor devices, in the development of a system for collecting and controlling information and in creating the software system for analysis, processing and visualization of information.

The dissertation has the following structure:

Introduction, which presents the problem under consideration, the main goals and objectives of the dissertation, as well as the general approach and methodology of the scientific research.

Chapter 1. Motivation and state of the research problem. This chapter presents the need for the development of IoT environments for intelligent livestock farming. In addition, the features of IoT platforms and cyber-physical and cyber-physical-social systems are considered, discussing the reference architecture of the Virtual Physical Space ViPS, through which the target system is modeled as an adaptation in the field of intelligent livestock farming.

Chapter 2. Development of an IoT platform for intelligent livestock farming. This chapter describes the software architecture and individual modules of the IoT platform for intelligent livestock farming. The technical means are described and the design and implementation of the sensor network, IoT sensor devices, software modules for collecting, processing and visualizing the dynamically incoming and accumulated information are discussed. This chapter presents the work on the implementation of several consecutive prototypes of individual components of the platform, according to the chosen research methodology.

Chapter 3. Results, analysis, discussion and future plans. The third chapter presents the results of the implementation of the prototypes of the IoT platform for intelligent animal husbandry. The implementation of the sensor IoT network and IoT devices is considered; the receipt, transmission and processing of unstructured, semi-structured and normalized data; the creation of two consecutive prototypes of the software environment of the Virtual Operations Center for processing, analysis, calibration and visualization of the received information. An approach for processing and analyzing the received data and conclusions about the behavior and activities of animals are presented. The directions for future development related to the development of the next version of the platform and ideas for analyzing and predicting the behavior of cows in free grazing are also commented on.

Conclusion – summarizes the results obtained in the dissertation research.

Acknowledgements

I would like to express my gratitude to my supervisors, Prof. Dr. Stanimir Stoyanov and Prof. Dr. Todorka Glushkova, for their help, support, ideas, guidance and recommendations during the conduct of my dissertation research. I am grateful for the opportunity to participate in research and educational projects that provide opportunities for the popularization of the results obtained.

I would like to thank the team from the Department of Animal Sciences of the Agricultural University and personally to Prof. Dr. V. Nikolov and Senior Assistant Dr. Radka Malinova as well as Senior Assistant Dr. Pencho Malinov from Department of Computer Systems for the trust they have shown in including me in the team conducting research in the field of intelligent pasture animal husbandry.

I thank the members of the department for their support and recommendations.

CHAPTER 1. MOTIVATION AND STATE OF THE RESEARCHED PROBLEM

1. Motivation for conducting the dissertation research

Obtaining biologically pure food products in an ecologically clean environment determines the need to develop intelligent systems for pasture cattle breeding. Modern digital technologies provide the opportunity for data analysis and decision-making in a dynamically changing environment, which provides the necessary basis for the development of successful intensive livestock farming [1]. Agriculture is becoming an increasingly relevant area of research in the field of IoT (Internet of Things) [2], CPS (Cyber-Physical Systems) [3]and CPSS (Cyber-Physical-Social Systems) [4].

The National Scientific Program for Smart Agriculture in Bulgaria, in its part for smart animal husbandry, sets as its main task the use of IoT for monitoring the environment, health, development, behavior and reproduction of cattle, in connection with the modeling of biologically appropriate breeding technologies. In free-range cattle breeding, control of the entire process is of particular importance due to the need for quick and timely intervention by the farmer to more fully meet the needs of the animals. However, this process is hindered by various factors such as: the remoteness of pastures from farms and settlements; difficult access to high-mountain pastures; insufficient internet and network connectivity in these areas; the need for continuous monitoring of large, hard-to-reach areas; the need to process and analyze dynamically incoming information related to the condition of the animals, as well as that of the pastures, and many others.

Based on established good practices and shared experience from specialists in the field, we set ourselves the goal of creating a prototype of a hardware and software platform and developing models for the behavior of cows in pasture farming. To conduct the research, it is necessary to solve a number of technological problems, namely: it is necessary to create a sensor network covering large areas; the sensors used must be able to offer an autonomous mode of operation for a long period of time; in addition to obtaining sensor data to verify the animal behavior model, additional physical observations are required, requiring human resources and the participation of experts in the field; after receiving the data, a process of targeted data normalization is necessary, according to the verification by specialists, etc.

Advances in hardware digital technologies and wireless network connections create the possibility of building energy-efficient, multifunctional and low-cost network devices. These devices are sensor nodes distributed in a certain geographical area. Sensor nodes cooperate with each other to realize the so-called sensor network. A sensor network can provide access to information anytime and anywhere by collecting, processing, analyzing and distributing data. In this way, the network actively participates in the creation of an intelligent environment [19].

An IoT sensor is essentially a device that measures a physical quantity and converts it into a signal that can be read by an observer or an instrument. The sensor receives a stimulus from the environment and responds with an electrical signal and the generation of digital information. Sensors measure a specific quantity, but to create a cyber-physical intelligent platform, it is necessary to combine these sensors into a complete **multi-sensor device,** where the information is collected, analyzed, processed and sent to the sensor network by means of a computing processor.

2. CPS and CPSS platforms

Nowadays ***Cyber Physical Systems (CPS)*** are gaining more and more fame and popularity in almost all spheres of business, education and people's lives. CPS are new generation systems that integrate computational and physical capabilities interacting with the real world through newly created and up-to-date models. The ability of technologies to connect and interact with the virtual and real world is formed at new levels including: calculations, control, communication, interaction and understanding [5] . In turn, ***Cyber Physical and Social Systems*** (CPSS) are a new generation of CPS , which also includes the social aspect. To achieve the most complete symbiosis between man and the computer world, CSP together with Io T, as well as modern network communications, provide the opportunity to design and implement CPSS , which system is based on and takes into account the human factor and timely interaction with the work and management of systems **Error! Reference source not found.**.

Providing high-quality and organic food is one of the main tasks in modern development. This leads to a constant increase and increase in requirements, rationalization and workload in cattle farms. The need for the introduction and use of automated intelligent systems is increasing, which can optimize the entire cycle of production and sale of products. The potential of existing systems managing production processes is greatly underestimated due to the lack of sufficiently effective communication and general intelligent management of the entire structure of information and services. That is why CPS and CPSS can radically change the situation by providing new opportunities and prospects. The topic of creating intelligent multi-agent CPSS systems in the field of animal husbandry is particularly important and promising, but due to the complexity of research and the difficulty in building such systems concerning the behavior of animal species, the area has not been sufficiently studied. The topic of creating and using CPSS systems for pasture cattle **breeding is particularly challenging for the scientific community.** The problems are related to the dynamic observation of animals in their natural environment, as well as to the formalization of their behavior and condition. This is not the case with the observation and management of processes related to cows raised on farms, since there the animals inhabit relatively small territories – barns, in which a controlled environment can be provided [7].

The problems presented by free-range cattle farming mainly concern technological implementation and difficult accessibility to a large area. This is the reason for directing the present study to this specific subject area. The scarce information related to the formalization of the behavior and condition of animals in free-range farming is our main motivation for working in this area. One of the goals of the study is to implement a test model for the formalization of animal behavior within a cyber-physical platform, as well as the application of this model in free-range cattle farming.

The Virtual-Physical Space (ViPS) was developed by the team of the DeLC laboratory at the University of Plovdiv. It is a reference architecture based on IoT, which can be adapted to various CPSS applications in various domains [9], [10]. The software components and agents in ViPS interact according to the conditions of the physical and virtual environment, as well as according to their knowledge and understanding [8]. Usually, when creating a specific ViPS application, individual components of the architecture are adapted, by adding and integrating modules specific to the subject area under consideration. The ViPS architecture includes two sets of components:

– ***General-purpose components:*** These types of components aim to provide common functionality for any CPSS application, regardless of the specific application domain. Adaptability is an essential characteristic of components. The concept of an IoT ecosystem is based on the ability of these intelligent objects to observe, detect, process, analyze, and respond appropriately to changes in their environment. The above capabilities make them autonomous, proactive entities that share knowledge and information with other IoT devices [11] .

– ***Specific components*** **:** The group includes components specific to application in the respective subject area - for example, agriculture [12] **Error! Reference source not found.**; education [12]; tourism [14], [15]and others.

ViPS provides options for storing these components in specialized repositories, making them an integral part of the overall architecture. The developed intelligent livestock farming system is a specific adaptation of reference ViPS architecture.

Cyber-physical systems integrate computer algorithms with physical processes and play an important role in various fields, including smart livestock farming. In the context of smart livestock farming, machine learning (ML) helps optimize production, monitoring, and resource management. [16]. The main advantages of machine learning in a cyber-physical environment are: precision, automated detection of anomalies (e.g. diseases or behavioral abnormalities in animals), monitoring of animal health, resource optimization and sustainable development (including analysis of environmental conditions and reduction of carbon footprint). There are also some problems and challenges, such as: access and quality of the received data; some computational limitations (e.g. in remote mountain farms), interoperability between systems using different technologies and software platforms; model training; cybersecurity, technical and financial issues. Different AI models can be used to solve different problems in intelligent animal husbandry, which we can summarize in the following areas:

– *Regression models* are used to predict animal performance based on various factors. For example, to predict milk yield based on the health status and feeding habits of the animals.

– *Methods for clustering,* which helps segment animals into groups based on their characteristics, behavior, health status, productivity, etc., allowing for better herd management.

– *Decision trees* through which it can be done classification and prediction of diseases by analyzing various characteristics of animals.

– *Neural networks (Deep Learning).* They are used to process complex data, such as images and sounds, for example for behavior recognition or image analysis to monitor animal behavior, detect wounds or other health problems. Reinforcement Learning can be used to optimize processes in real time, such as feeding automation.

Due to the increasing complexity, uncertainty, and size of data in many systems, conventional methods often encounter obstacles when trying to solve problems requiring decision-making and control. Deep reinforcement learning (DRL) is a data-driven method and is considered a fundamental application of artificial intelligence (AI). DRL is a combination of deep learning (DL) and reinforcement learning (RL). This field of research has been applied to solve a wide range of complex decision-making problems **Error! Reference source not found.**. DRL combines the feature representation capabilities of deep learning (DL) with the decision-making capabilities of RL, so that it can achieve full-featured control of the machine throughout the entire implementation process [17], [18].

The integration of intelligent technologies for process refinement is of particular importance for smart agriculture and in particular animal husbandry. The agricultural and in particular animal husbandry ecosystem is complex, multivariate and largely dependent on factors with low predictability. To meet these difficulties, this complex structure must be better understood through continuous monitoring, measurement and analysis of various physical characteristics and events. This is realized in a relatively easy way by analyzing the large volume of information with the help of modern information and communication technologies, which are used both for short-term and long-term management of agricultural and animal husbandry farms, as well as for large-scale environmental monitoring. In this regard, one of the most applicable technologies is WSN (Wireless Sensor Networks) [20]in combination with machine learning algorithms. WSN is built from a larger number of IoT nodes that are installed at key points and collect data before transmitting them to the base station for subsequent processing. However, for the large number of sensor nodes, scalable and efficient algorithms are needed.

The current dissertation work focuses on the modeling and prototyping of a CPSS platform for pasture livestock farming by applying various technologies to optimize cattle breeding. This study describes various problems arising in WSN regarding the application of technology in the field of intelligent livestock farming and the possibilities for their solution.

3. Conclusions from Chapter One

1. The development of intelligent platforms for pasture-based ecological livestock farming is of particular importance for modern development.
2. The application of CPSS technologies is suitable for the development of the target platform.
3. ML algorithms , and in particular DRL , on data obtained from appropriately structured IoT sensor networks is a successful approach for dynamically managing animal behavior and activity.

CHAPTER 2. DEVELOPMENT OF IoT PLATFORM FOR INTELLIGENT LIVESTOCK

1. Basic setup and approaches for building an intelligent livestock breeding system

The developed IoT environment for intelligent livestock farming is a specific adaptation of the reference CPSS architecture of the ViPS Virtual-Physical Space. Usually, when building a specific ViPS application, only individual components of the architecture are adapted, adding and integrating modules specific to the subject area under consideration. The ViPS architecture contains two sets of components – general-purpose and domain-specific. The first group is the general-purpose components. Their goal is to deliver common functionality for any CPSS application, regardless of the specific application area. An essential feature of these components is their adaptability. The concept of creating an IoT ecosystem is based on the ability of these intelligent objects to observe, detect, process, analyze and respond appropriately to changes in the environment. All these capabilities define them as autonomous, proactive units that are able to share knowledge and information with other IoTs and together to plan and make decisions to achieve individual or shared goals. In addition, they must be able to communicate seamlessly with each other in a network and be able to form a hierarchical network structure.

The second group includes components specific to the application in the respective subject area. ViPS provides options for storing these components in specialized repositories, thus making them an integral part of the overall architecture. In the next part, we will take a closer look at the second group of components that provide specific functionalities necessary for the functioning of the IoT platform for smart livestock farming. Due to the wide scope of the requirements, as well as the complexity of the tasks, it was necessary to conduct in-depth and detailed studies and analyses of both the overall software architecture and the individual components, nodes and connecting elements.

The initial analysis aimed to determine the appropriate architectural components that are necessary to implement a system capable of solving the previously set tasks and problems. Worldwide, there are various similar systems (and architectural solutions, respectively), which were analyzed as potential ones for solving the specific project. After the initial analysis, we defined 4 main directions for development and detailing the architectural model of the system, as follows (Fig.1):

- Design and implementation of a sensor network;
- Design and implementation of sensor devices (for livestock and pastures);
- Design and implementation of a system for collecting and controlling information flows;

– Design and implementation of an intelligent software system for analysis, processing and visualization of information.

The main problem in building the overall architectural model is based on the design and implementation of the first three layers of the system, which aims to provide non-normalized data to the intelligent models in the fourth architectural layer. Following the methodology of the current scientific research, the development of the individual components, as well as the overall platform, follows a step-by-step iterative approach. In the course of the work, various prototypes were designed, created and tested both in the construction of the sensor network and sensor devices, in the development of a system for collecting and controlling information, and in the creation of the software system for analyzing, processing and visualizing information.

In accordance with the above approach, I developed a step-by-step methodology that would help to consistently detect and solve the main problems, as well as parallelly analyze the interaction of the overall architecture with newly emerging problems. Initially, I focused on the type of final information on the basis of which the algorithms used could achieve better results. Research was conducted in the field of model algorithms and the appropriate ones for the present study were identified.

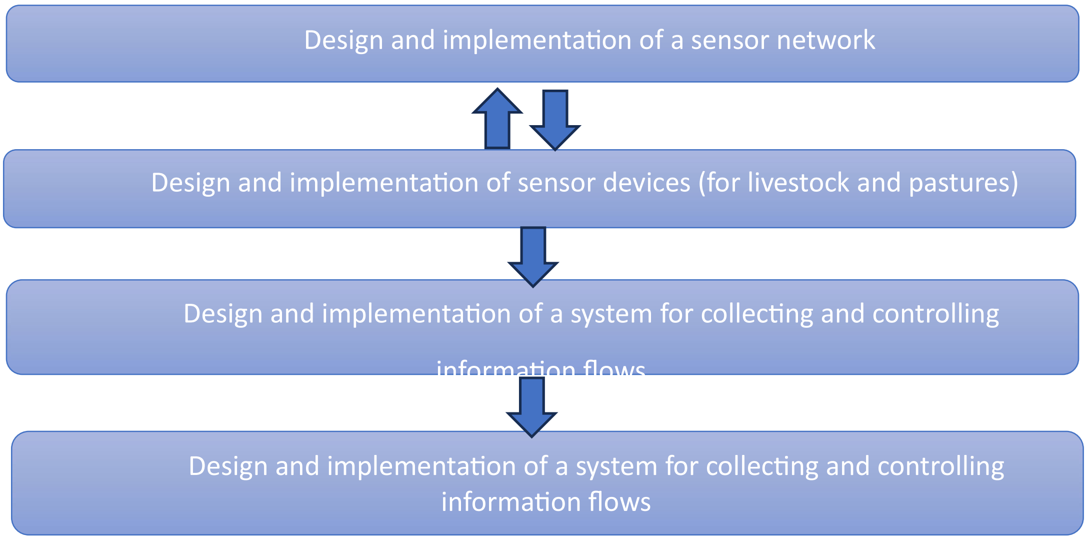

Figure 1*Approach to building the architectural model*

The next major problem is the collection of non-normalized information from animals and pastures. The research focuses on two distinct areas:

– building IoT sensor networks
– creating sensor devices for animals and pastures

The focus of the dissertation is on studying the behavior of cattle grazing in the open on wide-area pastures. Therefore, it is necessary to design and implement a large-scale energy-efficient sensor network based on a small number of repeaters with a large range. Based on the main problems and analyzing the technological approaches, we focused on an IoT sensor network based on LoRa technology, which allows data transmission over long distances, as well as maximizing energy efficiency. After choosing the technology and method of building the sensor network, the next serious problem was the design and implementation of dynamic, energy-efficient sensors with autonomous power supply and small in volume, which can be conveniently attached to each individual animal. Of utmost importance for the operation of the analysis algorithms is the collection and processing of information from a large number of animals. The number of animals studied significantly increases the model's ability for self-learning and, accordingly, accuracy. The main problems that we can define at this stage are difficult to solve, given the requirements set, as follows:

– Extremely high energy efficiency, allowing the sensors to operate autonomously for a minimum of 6 months.
– Implementing computing power into each individual sensor, allowing it to collect, process, and partially normalize information from each sensor in the sensor (offloading some of the system's intelligence to a low level).
– Selection of the right sensors to collect usable information for the needs of the project's ultimate goals.
– Minimizing the volume of information flows sent to the sensor network in order to achieve high reach.
– Small-sized sensors that can be attached to any animal in a humane manner, as well as ensuring that they will not interfere with the animal or contribute to its irritation.
– Exceptional strength and durability of the sensor, allowing it to withstand reactive voltages, physical shocks, weather conditions and animal behavior.

After establishing the main approach of the research, the underlying technologies, as well as the prototype implementation of the sensors and sensor networks, I continued with the parallel design and solution of the software architectural models, ensuring the processes of collecting, storing and normalizing large volumes of data. This information comes in a dynamic mode from each sensor and must be appropriately processed in an appropriate form to generate inferences and conclusions using statistical methods and AI. Analyzing the appropriate approaches and architectures for collecting, storing and decrypting sensor information, the conclusion was reached to use SQL databases with advanced scalability and speed capabilities. This choice is justified from the point of view of the scalability of the system and the incoming information per unit of time. I settled on this approach due to the problem of collecting information from N number of sensors and the coincidence of the time dimensions (i.e. several sensors can send information in one millisecond). It is of utmost importance that the initial storage of data provides a working model in which we can be sure that none of the transactions will be lost and all will be in a consistent and correct form for subsequent processing.

2. A detailed overview of the architecture of an IoT system for smart livestock farming

Based on the general overview provided in the previous section, here we will focus in more detail on the system architecture. As already discussed above, the overall system is built on a multi-layer architecture consisting of the following layers (Fig. 2):

- Sensors and sensor groups (for animals and pastures)
- Sensor network
- Infrastructure connectivity between the sensor network and functional servers.
- Server layer for primary information storage.
- Server layer for application databases (including relational and non-relational databases).
- Data processing and analysis layer (including systems and methods for analysis, processing).
- Applied functional layer for data systematization
- Client layer for visualization of information in a systematized form

This model provides flexibility and focus on individual problems distributed across a multi-layered software system and contains **three main components:**

- Static and dynamic sensors.
- Portable and infrastructure environment.
- Provision of management and analysis software.

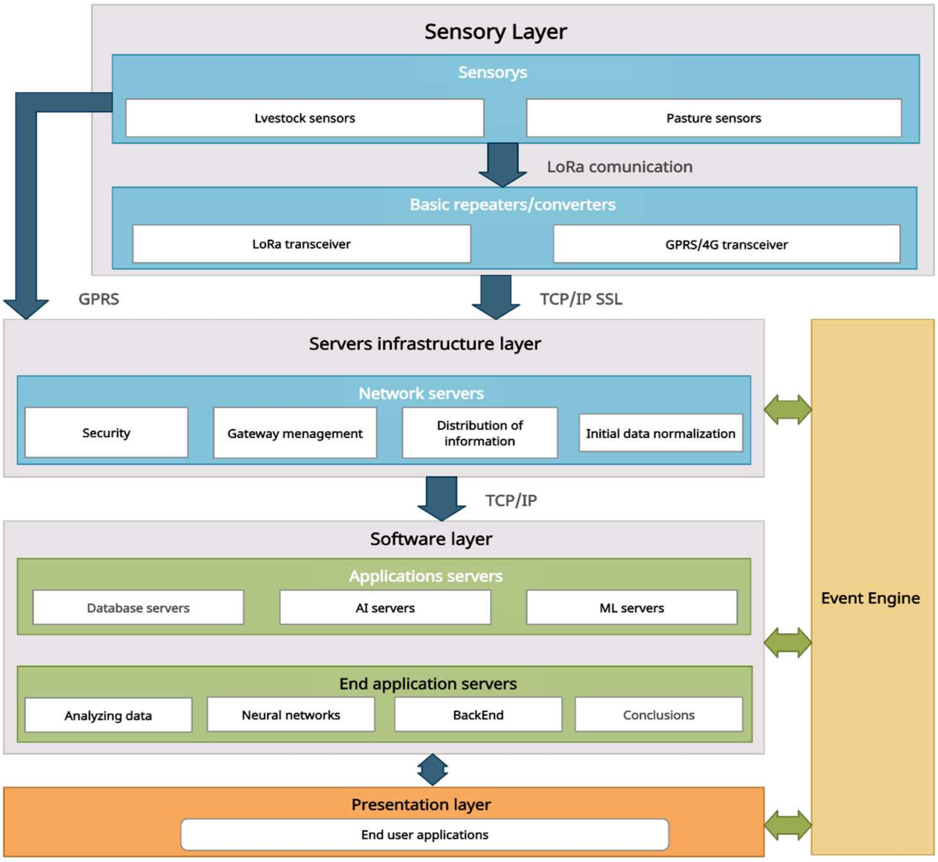

Figure 2. *Infrastructure diagram of architectural layers*

At the lowest level, sensor groups (a collection of sensors with different purposes) are based. They are divided into two separate parts: dynamic and static sensors.

Dynamic Sensors - Each animal has an IoT sensor device with a set of different sensors. The sensor device is attached to the animal by means of a strap that does not disturb or interfere with the normal behavior of the animal. Based on the measurements and the effect of these measurements on the result, several experiments were carried out on the size, location, weight and other parameters of the sensors. The final sensor device was designed in a way that does not disturb or interfere with the normal life cycle of the animal. The study allowed determine the optimal parameters at which the measurement does not disrupt the behavior or biological cycle of the cows. The design and release of IoT devices is of critical importance for the data, due to the so-called "noise" generated by the behavior of the animals after attaching the sensor device. This problem was solved through a number of tests of different designs and operations of the devices, which allowed us to ensure maximum comfort of the animals under study, as well as a high level of truthfulness and correctness of the information.

Static sensors - The second group of sensors is designed for static installation on selected pasture sites, thus analyzing meteorological data, as well as soil data and other physical parameters of specific pastures. These sensors have a significant impact on the overall integration of animal behavior parameters in relation to their environment and real-world indicators. Synchronizing the behavioral data of an individual animal with the habitat (pasture) it inhabits in a specific time range forms a complete information picture of the observed parameters.

The application of the two main types of sensors, as well as the synthesis and comparison of the input information, reveals the potential for generating a complete picture of the behavioral characteristics of individual animals, herd habits and other parameters, refracted through the prism of data about their environment. Both types of sensors are equipped with groups of sensors, reading elements and blocks for maximum accuracy in identifying individual parameters. Immediately, each sensor is implemented on the basis of a microprocessor, which has the ability to perform processes of primary normalization of the data received using mathematical and programming algorithms that help to derive primary conclusions and minimize the flow of output information. For the stable and long-term operation of the sensors, it was necessary to carry out a number of studies, as well as to test various approaches related to the selection of combinations of sensors, programming and mathematical algorithms. The final satisfactory results were achieved after testing and analyzing over 15 different models and combinations of software and hardware prototypes. The goal was to achieve the highest possible percentage of truthfulness and relevance of the information.

In the research process, not the least attention was paid to the humane attitude towards animals. This is a major additional parameter, making the research difficult, due to the different types of breeds and behavioral parameters of the breed itself and the specific individual. Based on over 40 test animals in different locations, breeds, ages and sexes, acceptable parameters for the normal integration of the sensory groups in relation to the animals were established.

In parallel with the sensor layer, analyses, tests and research are carried out in the field of **transport and server layers** of the overall project. Work on the main three layers is carried out in synchronous and asynchronous mode, which ensures maximum compatibility and saves time, due to the parallel solution of both specific for the individual layer and common for the entire system problems. In the process of work on the selection of appropriate infrastructure solutions for data transfer, detailed studies of the available technical solutions were carried out, as well as an analysis of the specific problem area. As a result, three important requirements were established:

- Need for maximum sensor network coverage.
- Maximum energy efficiency of each individual sensor.
- Use of the announced free radio frequencies for data transmission, meeting all European and international standards and requirements.

At the design, testing and analysis stage, a number of problems were identified in the use of most standard technologies, such as WiFi, Bluetooth, Zegbu, GPRS, LoRa, etc. The analysis led to the selection of two technologies that solve most of the problems - LoRa [21]and GPRS. As a result, we chose LoRa as the main technology for transmitting information from sensors to sensor networks. The technology provides coverage of up to 10 quadrants of kilometers with one central station (according to the localization and geographical features of the terrain), as well as a linear increase in the range without restrictions by adding additional stations. On the other hand, GPSR communication, despite some shortcomings, provides a large part of the necessary functionalities. This type of transmission technology is suitable for smaller groups of animals, ensures the operation of IoT sensors using existing GSM stations provided by the operators of these services. Despite these advantages, problems have been identified, such as: lack of coverage of GSM towers in some regions; increased energy consumption of sensors; significantly increased cost of sensors; increased difficulty of implementation.

For the implementation of the project and based on all legal requirements and conventions, a frequency range of the so-called open/free to use frequencies was selected, as follows 868Mhz for Europe and 433 for other countries with different regulations. The frequency range complies with local state regulations for radio broadcasting. The second studied technology GPS connectivity is oriented towards other frequency ranges GPRS - 850/900/1800/1900MHz. The achieved results were relevant to the set goals and exceeded preliminary expectations, reaching extremely good radio conductivity with no more than 12% transmission loss in territories and connectivity up to 10km. The above-mentioned studied approaches and technological solutions allowed us to optimize the software and hardware components for maximum energy efficiency and reliability. We achieved an average of **9 months** of battery life of the dynamic sensor groups when sending data every 10-20 minutes.

The third main component is related to the creation of software infrastructure, data analysis, use of appropriate algorithms, event management, etc. As a consequence of data collection, real-time analysis and presentation of sufficiently accurate conclusions based on the overall information, the design, analysis and design of software layers and their ability to ensure the processing of the incoming volume of semi-normalized information have significantly deepened. Providing data to the servers from the sensors, through sensor networks, the software layer is designed and based on modern technologies, which allows it to process large volumes of information in parallel, as well as analyze information in real time. A study has been conducted on the application of various statistical and AI algorithms (in particular, "Deep Reinforcement Learning"), in order to allow the system to analyze and make decisions based on historical, statistical and newly obtained information. Tests were carried out on a number of machine learning algorithms and other tools and technologies related to the subject area, with the goal of continuously increasing the reliability of the conclusions and analyses provided by the system.

The timely optimization of each of the mentioned layers, based on real tests and observations, as well as verifications by zooengineers and technical engineers, allowed me to optimize every aspect of the project, experimenting with many technological, conceptual, mathematical and other solutions and tools. By optimizing each experiment based on previous studies and achieved results, the goal was to reach a high level of accuracy of the conclusions provided by the overall system.

3. Interconnections and description of components and layers, communication, protocols, connection method

In continuation of the previous part, presenting the infrastructure layers of the system and their construction, we will continue the process of detailing the interconnections and methods of communication between the individual layers. The following figure 3 presents a generalized communication model, which provides a general view of the connectivity and interaction between the individual layers and components. The individual layers, the connectivity between them, as well as the types of communication protocols and technologies for the implementation of continuous and stable exchange of information between the end sensors and the users using the system are visualized. The complexity of the system predetermines the conduct of a thorough and detailed analysis in the structuring and differentiation of the individual layers and communication between them.

As can be seen from Figure 3, starting from the lowest level, the LoRa communication technology has been chosen for the connection between the end sensor groups and sensor networks. LoRa is a physical private radio communication technology. It is based on spread spectrum modulation techniques derived from spread spectrum technology. The technology provides a communication solution for long range, low power, flexible bit rate and low signal-to-noise ratio to interference [22]. As an extension of LoRa technology, both for communication between sensors and sensor networks, and for communication between sensor networks and the infrastructure layer for managing the information coming from Gateway stations, as well as the Gateways themselves, the LoRaWAN wide area network is used. LoRaWAN defines the communication protocol and the system architecture of the connectivity [23]. LoRaWAN is an official standard of the International Telecommunication Union (ITU), ITU-T Y.4480.

LoRa and LoRaWAN jointly define a low-power, wide-coverage network protocol designed to wirelessly connect battery-powered devices (sensor groups) to the Internet in regional, national or global networks. The advantages and focus of technology cover key requirements for the "Internet of Things" (IoT), such as: the ability to have two-way communication, communication security and the ability to be mobile and localized. The low power used, the low bit rate of sending and receiving data make the standard the most applicable from the point of view of the developed IoT platform. The communication speed from sensor groups to sensor networks and vice versa varies from 0.3 kbit/s to 300 kbit/s per channel.

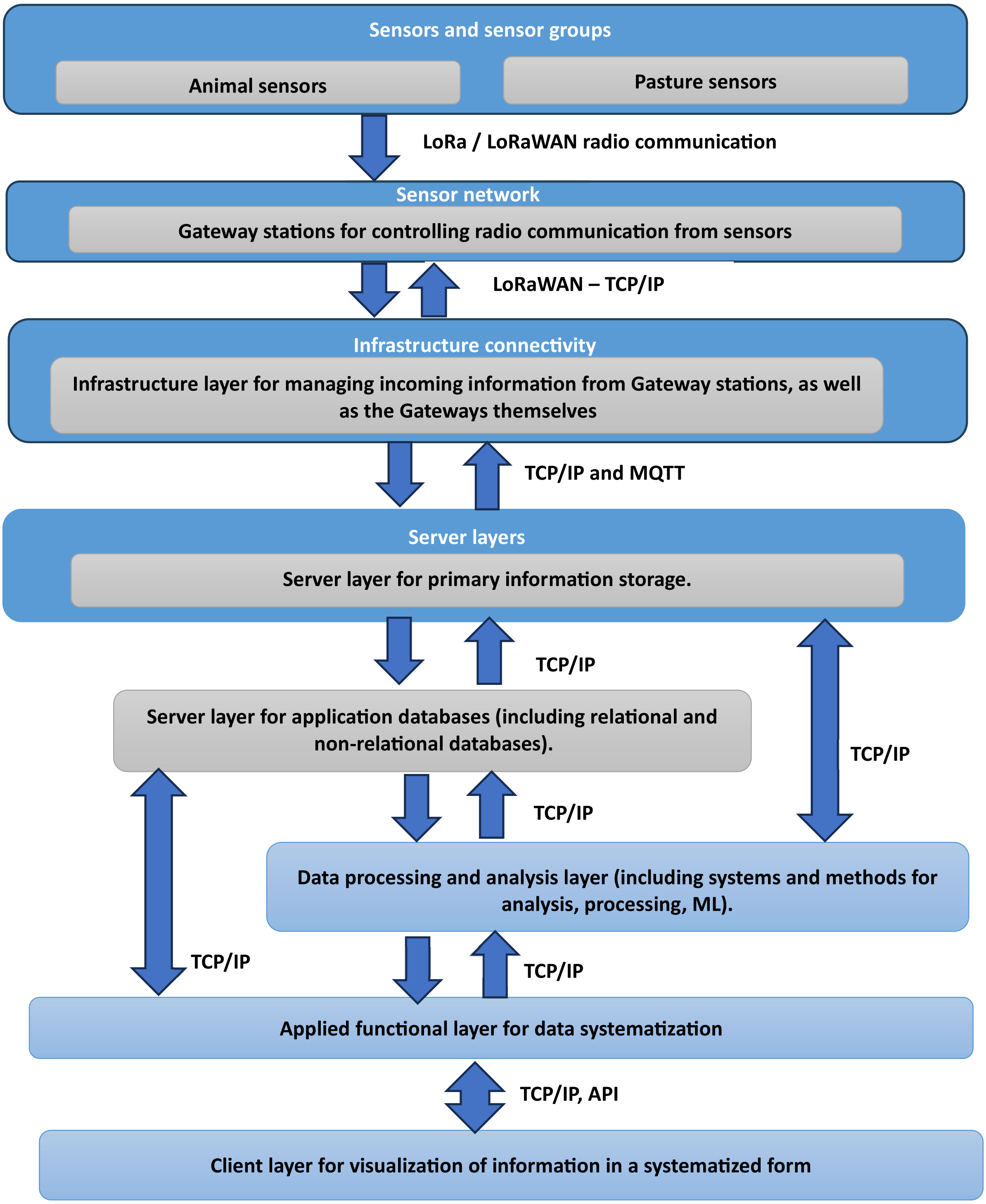

Figure 3*Diagram of the connections between the layers of the system*

The next level of infrastructure connectivity of the base layers to the server layers is implemented using TCP / IP and MQTT protocols. Communication between the various server sublayers, as well as between the main ones: Data processing and analysis layer, applied functional layer for data systematization and End-client layer for information visualization, are based on the use of TCP / IP protocols. The mentioned layers have a need for constant, two-way exchange of large amounts of information with reduction and correction of errors during sending, which are fundamental features and needs of the TCP / IP protocol. They are built on servers equipped with broadband network unlimited connectivity, due to which there are no difficulties in transferring large amounts of information.

4. Technical means and implementation

In the current section, detailed attention will be paid to the research conducted and the results achieved for the selection and implementation of each of the system layers.

4.1. Design and construction of IoT sensor networks

To achieve the main goal, two aspects are defined in the implementation of the IoT platform - collecting information from each cow and processing and analyzing the collected information. That is why the initial efforts and studies were focused on the principles, ways and methods of collecting information. By studying a large set of existing solutions, the following several approaches were formed to solve this task:

- *Approach 1* - Remote monitoring of animals using high-resolution intelligent video cameras. The cameras are installed in relative proximity to the animals, and then, using algorithms for recognizing specific animal individuals, as well as algorithms for recognizing behavioral patterns, semi-normalized data is provided to servers for data processing and analysis.
- *Approach* 2 – attaching individual sensors to each individual animal, which sensors collect information from the animals' behavior. After a certain period (the period can hardly be longer than 7-10 days), the sensors are removed from the animal and, via a cable, the data is downloaded to servers for information analysis.
- *Approach 3* – Attaching individual sensors to each animal that collect information about its behavior. After the animal passes in close proximity to a reading device (mounted, for example, on the barn door or on a feeder in the pasture), the collected data is downloaded wirelessly and sent to servers for data processing.
- *Approach 4* – Attaching individual sensors to each animal that wirelessly send information in real time or at specified intervals to a sensor network designed and installed within range of the sensors. The sensor network receives information from the animal sensors and sends it in real time to servers for processing the information.

Cattle are fed and grazed in open pastures, often at considerable distances from the farm, for the majority of their time. This requires solutions to some specific problems such as:

- Inability to care for animals for long periods of time (sometimes several weeks)
- Long distance of cow herds from farms
- Large number of animals studied
- Large areas for grazing animals, mostly based on rugged geographical areas
- Need for information to be available for each animal at short intervals (no more than an hour)
- High resistance of sensors and sensor networks when operating in external conditions such as moisture, high or low temperatures, physical damage, etc.

Cattle spend most of the year in the wild, which automatically excludes *Approaches 1 and 2,* in which the animals must be accessible to video surveillance cameras or be frequently serviced by farmers who remove the sensors and extract the information from them. Continuing the analysis with *Approach 3,* it was found that it cannot be implemented due to the technical impossibility of the sensors to operate autonomously in the information collection mode for a period of 7-8 months, as well as the need to deliver this information in short periods of time (maximum an hour), and not once at the end of the grazing period. The logical continuation of the comparative analysis brought out the last *Approach 4 as a suitable option for solving the problem.* The approach provides a solution to all the above-mentioned problems, but unfortunately also generates new problems, such as:

- Need to build a sensor network consisting of gateways based on large pasture areas.
- Need for autonomous uninterrupted power supply for receiving devices
- Need for high range on each device
- The need for a technological capability for an IoT device to receive and process information from multiple sensors.
- The need for each IoT device to connect to servers for information collection and processing.

To solve the above problems, several basic communication technologies and standards for connection between sensors and receiving devices were investigated:

- LoRa - physical private radio communication technology. It is based on spread spectrum modulation techniques derived from spread spectrum technology.
- GSM - Global System for Mobile Communications is a standard developed to describe the protocols for digital cellular networks used by mobile devices, such as mobile phones and tablets [24].
- Wi-Fi – a set of wireless network connectivity protocols based on IEEE 802.11 standards, which are typically used for local networking of end devices and their access to the Internet [25].
- Zigbee - based on a specification for a set of high-level communication protocols used to create private networks with small, low-power digital transmitters [26].
- Bluetooth - a standard for short-range wireless technology that is used for data exchange between fixed and mobile devices over short distances and building personal area networks.

The choice of a technology suitable for the purpose of the study is based on a comparative analysis between these communication technologies and standards in terms of their range, energy efficiency, price, number of served IoT devices and scalability, purpose, sustainability and size of the information packages. From the point of view of the most important parameters - range and energy efficiency, I focused on LoRa and GSM technologies. For the needs of the requirements of the developed platform and transmission environment, these are the two most necessary and insurmountable factors. Of course, each of the technologies has a number of disadvantages, which is why I continued the analysis of the selected two technologies, which determines the design and implementation of IoT sensors and sensor networks. In conclusion, the most suitable for the subject area with its predominant advantages turned out to be the LoRa technology for the design and construction of sensor networks, which is fundamental for the work on prototyping the IoT platform for intelligent pasture livestock farming.

4.2. Design and construction of IoT sensor devices

The next step in the implementation of the platform is the design and creation of IoT devices containing certain sets of sensors that have the ability to collect and primary process the data sent to the sensor network. The designed IoT sensor devices must be attached to each individual animal and, through the sensors and microprocessors implemented in them, be able to analyze the primary information, present it in a semi-normalized form, and then send it to the sensor network.

The analysis, design and prototyping of IoT devices are carried out in parallel with the analysis and design of sensor networks. This was necessary from the point of view of the factual analysis for the use of a single communication environment for connecting devices and the sensor network. After choosing a single communication technology (in this case LoRa), the main component for the implementation of the multi-sensor device was established. The working approaches used and the related problems in the implementation of the IoT device (IoT node) determined the need to carry out activities in the following several directions:

- Determining the necessary functionalities that the IoT device must perform.
- Determining the sensor groups that the device must have to implement the defined functionalities.
- Defining the overall architecture and operation of the IoT device
- Determining the algorithmic dependence between the sensors and the corresponding microprocessor device embedded in the IoT node.
- Solving problems related to energy efficiency, as well as the industrial design of the IoT device.

The next step in the design process of the IoT device is to determine its architecture and the associated sensors for reading and collecting data for each animal individual. To implement the prototype of the multi-sensor device, we use conventional sensors that are available for use, focusing on the main problems that the device must solve and, accordingly, the information that must be processed for: the location of the animal; the distance traveled per unit of time; the behavior of the animal, its actions and physiological state. In the process of work , it was found that there are no sensors that can directly diagnose the above-mentioned information. This developed my research in the direction of selecting several sensors through which the information can be combined and analyzed, as well as to realize certain conclusions in a semi-formalized primary form.

Solving this problem requires obtaining additional expert information, which is why I held multiple meetings and consultations with zoo engineers and specialists in animal husbandry and behavioral analysis. This provided the opportunity for a more complete understanding of animal behavior in the conditions of the considered cyber-physical environment. After completing the initial analysis of the overall structure, as well as the possible sensors to be used, the architecture of the IoT device was determined (Fig. 4).

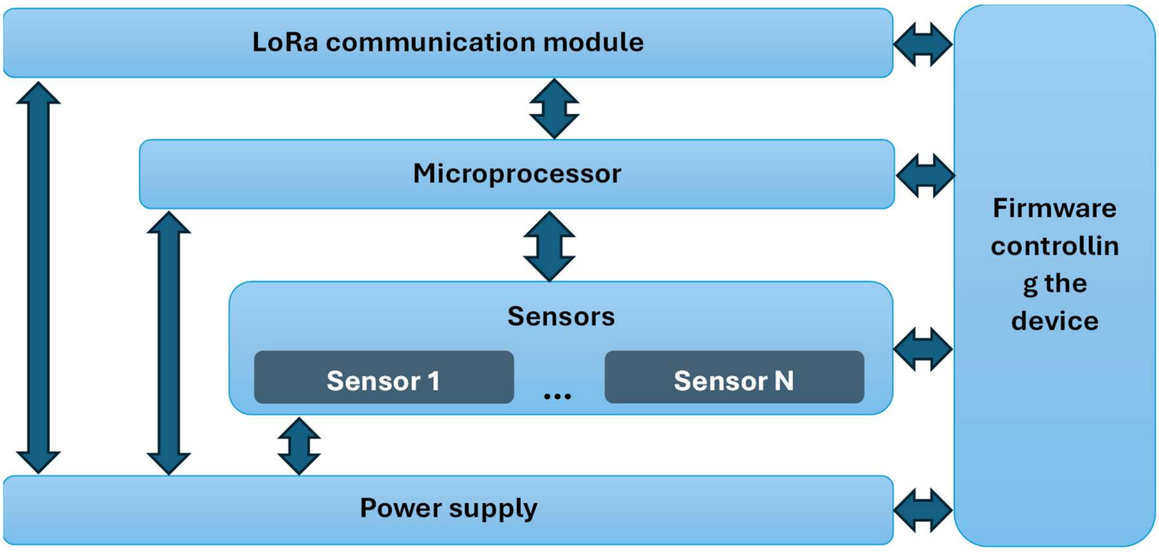

Figure 4*Architecture of an IoT sensor device*

The structure determines the entire process of the device's operation. The main technological unit is **the Microprocessor,** which is involved in the collection, control, processing and sending of information, as well as the operation of the entire device. **The communication module,** in turn, is also a microprocessor device with its own internal processor, but its only task is to receive the synthesized information from the main microprocessor, process it, establish a connection with the sensor network and send the information. Then it waits for confirmation of the completion of the sending and ends its cycle until the next iteration. **The power supply unit** takes care of distributing a sufficient amount of energy to all modules, and this process is strictly controlled by the main microprocessor. The control of this module is important for maximizing the energy autonomy of the IoT device.

The practical implementation of the IoT sensor device also went through several steps, which were directly dependent on the iterative development of the entire project. LoRa technology was logically chosen for the communication module in the device, with which communication between devices in the sensor network is also implemented. In accordance with the Communication Module, the main microprocessor was selected, to which the following requirements were set: low power consumption; a sufficient number of digital and analog communication ports; support for various types of communication protocols (necessary for connection with sensors); availability of sufficient computing power for processing sensor information; availability of the possibility of easy reprogramming and performing tests with different types of firmware. After analyzing over 15 types of microprocessors that meet the set requirements and over 60 tests and measurement experiments, the microprocessor device with the best complex indicators was selected, which to a significant extent meets the set requirements.

The next step required research in the field of energy sources (in this case batteries) and electronic modules, providing high efficiency (possibly over 90%). The main problem in the selection is the optimal and stable operation of all modules of the device in relation to the size of the battery and the overall autonomous operation of the device. As a result of numerous experiments, a suitable option was selected that met the specified conditions.

The final step in the implementation process involves selecting appropriate sensors, creating and implementing algorithms to analyze the information from all sensors, and providing semi-normalized output data to be sent to the sensor network for post-processing. In the next section, we will examine the process of selecting sensors and sensor groups, which is of crucial importance for the implementation of the project.

4.3. Analysis and selection of sensors and sensor groups

Analyzing information and developing models related to animal behavior and life cycle requires continuous processing of data related to the location of the animal, the distance traveled by it per unit of time, its behavior, determined by its movements and activities. Studies initially focused on reporting the location of the animal and the distance traveled per unit of time. Two main technologies can be used to solve this problem: using a GPS device or using triangulation technology [27]. In the conditions of remote pasture farming, the more appropriate solution is to use a GPS sensor that receives signals from the global GPS network. The triangulation model is very unsuitable, since it is necessary for each IoT device to have a connection with at least 3 ground stations from the sensor network, and the processor to be able to perform extremely complex triangulation calculations to determine a single position. On the one hand, this would slow down the operation of the sensor device and would violate energy efficiency. On the other hand, the use of this technology would slow down the data transfer in the sensor network. That is why GPS technology was chosen. Due to the wide variety of such sensors available, a specific sensor was selected that met the following requirements:

- high energy efficiency;
- high reading accuracy;
- high reading speed;
- minimum size.

The measurement of the distance traveled by each animal is based on elementary mathematical calculations based on the sequential measurements of the GPS sensor.

For measuring and analyzing the activities and behavior of the animal, the main time was allocated for analyzing sensors and sensor groups that have the ability to measure parameters [28]. In the initial phase of the analysis, I studied the possibilities for measuring the behavioral characteristics and specific parameters of the animals that need to be examined. The positioning of the sensor on the animals is also of great importance [29]. In conclusion, it was found that the best place to attach the sensor is on the neck of the livestock. This is the place where the sensors have the ability to record changes in activities and behavior.

Due to the living conditions in pasture livestock farming, we excluded all sensors that require invasive placement. It was found that in terms of accessibility, capabilities, energy efficiency and applicability of the various sensors, there are no ready-made solutions and sensors that provide the comprehensive necessary information. This determined the need to explore possible combinations of sensors that would take up little space, provide the necessary information and be energy efficient. Based on previous observations and experience gained from working on similar systems, we decided to place the IoT sensor device on the animal's neck.

In the first version of the IoT device under development, given the need to obtain complete information, we included the following non-invasive sensors:

- Sensors for measuring the number of steps
- Sensors for measuring acceleration along three axes
- Sensors to measure the positioning of the device relative to the earth's surface
- Sensors for measuring the earth's magnetic field
- Vibration sensors
- Pressure and thrust sensors

During testing, it was found that the IoT device was not energy efficient. Considering the way the sensors work, as well as the deviations in the data, it was decided to remove the sensor for measuring the number of steps. After conducting experiments and analyzing the results, devices were prototyped with a different set of the following relevant sensors:

- Acceleration measurement sensors
- Sensors to measure the positioning of the device relative to the earth's surface
- Sensors for measuring the earth's magnetic field
- Vibration sensors
- Pressure and thrust sensors

More than 10 prototypes of the IoT device were made with different models and types of sensors, and the results obtained were analyzed according to several parameters: data accuracy; speed of operation; reported parameters; ability to perform comparative analysis based on all parameters; stability of the sensors and low energy consumption. Each prototype was also analyzed in terms of the possibilities of achieving high levels of consistency and accuracy of information, which statistical and AI algorithms can process and draw conclusions as close to the truth as possible.

5. Design and implementation of software tools for information collection

The next step in the design and construction of the sensor network, IoT sensor devices, the work on the implementation of the project continued with the creation and implementation of the models and approaches for collecting, normalizing and processing the dynamically incoming data. Based on the information flow arriving from each sensor, as well as the service information sent from each point of the sensor network, several basic requirements for these software tools were established, as follows:

- Recording and processing of semi-normalized information arriving from sensors
- Normalization and re-recording of information as extreme values
- Working with many sensors that send information per unit of time
- Development of different types of models for the normalization of information according to different prototypes.

– The ability of the process to intercept information without dropping transactions, despite the frequent arrival of transactions (sometimes within a millisecond).

– Stability and relevance of data with a high level of fidelity and no possibility of errors

In this stage of preliminary preparation, efforts were focused on implementation using classic relational databases, such as MSSQL, PostgreSQL, MYSQL . The selection of specific relational databases was focused on those that have proven their stability, resilience and relatively easy maintenance. After a detailed examination of the implementation databases, it was concluded that an additional buffer "transport layer" based on Kafka [30] is needed. This layer has the ability to absorb and buffer an almost unlimited amount of unnormalized data, which can be sent to the relational database for additional processing and normalization via a communication bus through the B ackend layer and micro-services. Therefore, the process REF _Ref180318602 \r \h * MERGEFORMAT follows the following logic:

A. The IoT network sends the received data from the sensors to the distribution layer. This layer aims to receive the semi-normalized information and distribute the data to specific Kafka “topics” . Due to the two main prototypes of IoT sensor devices, the information is distributed to different topics.
B. After receiving the primary information and storing it in Kafka, the data is distributed, processed, and initially analyzed to a relational database using microservices.
C. When the information is written to the relational database, it is already defragmented into specific values and allows for final data processing.

The implementation of Kafka provided additional information for choosing a specific relational database. The choice is based on various factors, such as: speed; price; capabilities; support and additional functionalities related to IoT. After conducting various tests and practical experiments, we came to the choice of **PostgerSQL** [31]. PostgreSQL is an open-source relational database that offers powerful tools for processing sensor data. The advantages it provides are related to the support of complex data types (JSON, JSONB, arrays, geospatial data, etc.), as well as the ability to process large volumes of data using tools such as table partitioning, which is useful for large-scale sensor networks. It also supports secure authentication, encryption, and rights management mechanisms that are important for protecting sensor data. In terms of data accuracy with an intensive flow of sensor information, PostgreSQL provides ACID compatibility (consistency, isolation, and durability). In addition, PostgreSQL integrates well with analytical platforms such as Apache Kafka, TimescaleDB for temporal data, Grafana for visualization, etc., and for the analysis of the received sensor data, it supports complex SQL queries, aggregations, and calculations. PostgreSQL can execute parallel queries, which speeds up the analysis of large volumes of data, with the addition of the PostGIS extension, it can process geographic information, which is useful for GPS sensors. Along with the listed advantages, we must also consider some problems and challenges for PostgreSQL, such as the fact that with extremely large volumes of data (for example, millions of records per day) delays may occur, and with insufficient disk space and RAM, PostgreSQL can become heavy for the system when processing data in real time. In addition, PostgreSQL does not have built-in ML algorithms, which limits direct analysis and requires integration with external tools using Python or others.

The stability of information upon arrival and processing in the central servers of the system is based on the primary distribution layer with the ability to receive and record data from hundreds of thousands of sensors per unit of time. The layer takes care of the distribution of information by topics in the Kafka buffer environment, after which the microservices crawl the received information, analyze it, divide it into parameters and record it in the relational database for further analysis and use by the intelligent agents of the system. The approach provides extremely high scalability of the number of sensors, speed, stability and minimized possibility of data loss. In the event of a possible problem in the PostgreSQL relational database or a problem with specific data, the entire system has the ability to check and additionally transfer the primary information stored in Kafka. This model of defragmentation of data recorded at a different level of its processing ignores the possibility of compromising information or its loss.

Examples of information received from the IoT network by layers:

✓ **Information *received and processed by sensors, and transmitted through the sensor layer***

- Unique device number containing model and integrated sensors: **260BC5D0**
- Date and time of information retrieval: **2024-10-20T09:27:04.761594516Z**
- Non-normalized sensor information for the individual device: **sp4oQkfaxUEbAFgAAAAAAAAAAAAAAA==**

✓ **Distribution and semi-normalization of data from the distribution layer to Kafka:**

- The individual number is recorded in the same attached form: **260BC5D0**
- Date and time of information disclosure: **2024-10-20T09:27:04.761594516**
- The semi-normalized data from the device's sensors:

b29e284247dac5411b00580000650000036008012000340 56

✓ **The normalized data information is distributed and stored in the relational database using microservices:**

- The individual number is recorded in the same attached form: **260BC5D0**
- Date and time of information disclosure: **2024-10-20T09:27:04.761594516**
- Normalized information recorded in the database prepared for visualization and/or analysis: **1: 42.1249759; 2: 24.23158; 3: 40626; 4: 16936 6: 55879 7: 16837; 8: 27; 9: 88; 10: 0: 11: 0: 12: 42.**

The number of parameters and their meaning is determined by the device model. The system receives the information and parameter values through its unique number.

After receiving, recording, and initial analysis of the overall information, as well as the metadata for each individual sensor, the data is recorded in the relational database and awaits further processing and visualization.

6. Design and implementation of software infrastructure for information processing and visualization

So far, we have built all the layers, starting with sensors and sensor networks, moving on to transmission media and interfaces, as well as partial storage and processing of the entire information flow. The last step in building the IoT platform is the development of a software system including the implementation of business processes, connection to the database, implementation of user interfaces, intelligent agents and other technologies for analysis, processing and provision of the final information in a suitable form to the end user. During the technological process for building the software environment, we decided to use Java for several main reasons: technological compatibility with the other components of the ViPS reference architecture; the openness of the technology; the extremely large set of libraries and tools facilitating the implementation of the software product; ensuring multi-threading and capabilities for managing IoT devices; the ability to run the compiled code on different hardware platforms and operating systems; excellent integration and integration libraries with the PostgreSQL relational database.

The diagram of the technological processes in the development of the software implementation can be traced in the following diagram (Figure 5).

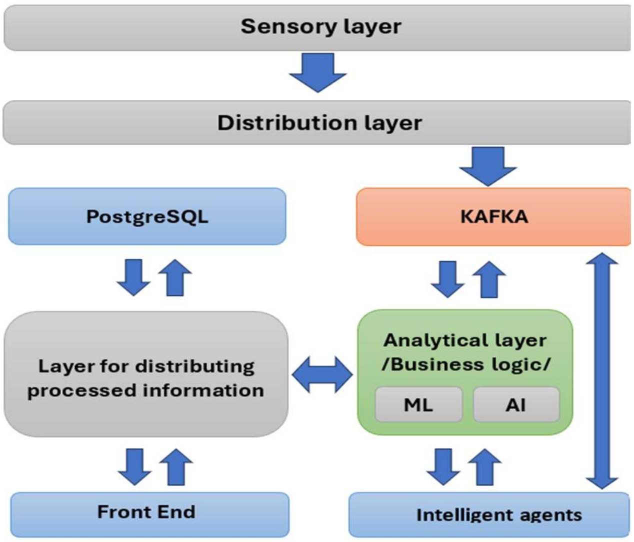

Figure 5. *Software architecture*

The sensor layer includes all the end sensors, as well as the devices collecting the sensor information. Each of these devices transmits the received information via TCP / IP communication to a specially designed server that manages the collecting devices. Due to the architecture of the LoRa used WAN network, the collection devices also receive sensor information from sensors that are not part of the sensors of our study. That is, the network is open to all devices using the LoRa radio environment. From this point of view, the incoming sensor data is contaminated by external ones, which is taken care of by the server for managing the collection devices and the Distribution layer. **The Distribution layer** has three main target functionalities: accepting the incoming information from the sensor network and ignoring incomplete transactions, erroneous transactions or those that were not sent by the sensors in the current ecosystem; processing and decrypting the information arriving from the sensors, as well as preparing the information for subsequent action; distributing the information by topics and sending it to Kafka . Distribution by topics is an extremely important process for subsequent actions and processing of the information. After receiving and distributing the information by topics in Kafka , the system completes the first and main cycle for delivering the data to the server level, as well as decryption and primary distribution. **The analytical layer,** as part of the ViPS Analytical Subspace , contains the applied business logic of the system, as well as components for automated information analysis. The detailed analysis of the information, as well as the overall business logic of the system, determine the overall functioning of the IoT platform. The learned information is defragmented, analyzed and processed. Conclusions are drawn based on specific data and compared with the entire array of information stored in the system. The analytical layer directly and indirectly communicates with all other layers at the software level, providing synchronizing and specifying information to each of them. The analytical layer directly corresponds to **the Processed Information Distribution Layer,** which distributes the information submitted to it in the relational database, as well as provides information to the user FrontEnd layer. This layer is key to the correct addressing of current and historical information to and from the relational database and, respectively, to and from users using the system.

Agent-oriented approaches are particularly suitable for building CPSS applications. The main components of any ViPS-adapted system are the assistants, implemented as rational agents with BDI architecture. The agent itself is a software component with proactive, context-aware intelligent behavior, which functions depending on the dynamics of the environment and is able to provide the necessary functionalities. Services are a suitable solution for providing certain functionality to the system, but by their nature they are static and not sufficiently adaptive. Therefore, in ViPS agents include appropriate interfaces to services in their internal architecture, thus enabling the space to function as an intelligent ecosystem, open to continuous expansion with new services. In the specific ViPS adaptation, **intelligent agents** projectively take actions based on different scenarios. Their direct access to Kafka and the Analytical Layer, as well as their native access to the Data Distribution Layer, the relational database and the Front-End, allows them to make proactive decisions and send messages along the entire chain of the software system. The approach of proactive interaction with the components and users of the system facilitates the overall analysis of information, while also ensuring a higher level of project autonomy.

The user layer (Front-End) has a primary purpose for visualization and management by users of the fully normalized, user-oriented reading information and conclusions provided by the system. The layer is implemented entirely using WEB technologies, which allows working with the system to be carried out using various types of devices such as computers, tablets, smartphones, laptops, and others. The specially designed WEB interface provides easy access, as well as systematization of information for entire groups of users with similar profiles, as well as for individual specific users. Intelligent agents also have access to the user interface in order to be able to visualize specific events in real time, as well as historically, and to provoke users to pay attention and, if necessary, to take certain actions.

The structure of the software system is designed with the possibility of a high level of scalability regarding: incoming information from the sensor network from an unlimited number of sensors; analysis and processing of the stored information; multiple concurrent user sessions.

During the development of the software implementation, attention was also paid to information security, using up-to-date tools to enhance it.

7. Conclusions from Chapter Two

During the technological construction of several consecutive prototypes of the IoT platform for intelligent livestock farming, we can draw the following conclusions:

1. The use of LoR and GPRS technologies provide the necessary stable transmission environment for creating an IoT ecosystem for remote pasture animal husbandry.
2. The proposed methodology for the development of IoT devices provides the opportunity to create two energy-efficient prototypes that ensure stable reception, initial processing and transmission of dynamically incoming information.
3. The proposed software framework enables the creation of the software implementation of the IoT environment, including the software components for collecting, processing and visualizing information.

CHAPTER 3. RESULTS, ANALYSES, DISCUSSION AND FUTURE PLANS

The development of the overall model and concept of the system is divided into several main phases, according to the requirements and the analysis of the main information and technological dependencies. This chapter describes the main phases of project implementation from the point of view of acquisition, processing and reconciliation of the overall information flow and the accompanying additional data.

The complexity of the development and implementation of several prototypes of the IoT platform determines the need for teamwork of various specialists - in computer science, networks, zoo engineers, etc. When working on the topic, I worked as part of the team for the implementation of the National Scientific Program for Smart Agriculture, in its part for smart animal husbandry, which was formed at the Department of Animal Sciences, Agricultural University, Plovdiv. The results presented in this part are related to my work and responsibilities on the project, but some of them were achieved in joint work and coordination with the other members of the team. The results obtained have been published and presented to the scientific community in co-authorship with the representatives of this team.

For the needs of the research area and the study of the results, we will examine in more detail the following areas of the development process:

- Building the infrastructure model and system architecture of the intelligent livestock grazing space.
- The construction of sensor groups and sensor devices and the creation of a local infrastructure for data collection.
- the development of the architecture of the Virtual Operations Center, which includes the software and presentation layers of the infrastructure model of the developed intelligent space.
- analyzing data from the dynamic observation of the studied units and discovering statistical dependencies between real physical observation and sensor data by using two implemented prototypes of sensor groups.

1. Implementation of the main modules and components of the platform

The software infrastructure of the system is based on a multi-layered model of implementation and integration between the individual layers. Due to the complexity of the project, we sought to a large extent an optimal infrastructure and multi-layered-differentiated segmentation of the overall system:

- Sensors and IoT sensor devices.
- Sensor IoT network.
- Infrastructure connectivity between the sensor network and functional servers.
- Server layer for primary information storage.
- Server layer for application databases (including relational and non-relational databases).
- Data processing and analysis layer (including analysis systems and methods).
- Applied functional layer for data systematization.
- Client layer for visualization of information in a systematized form.

Sensors and IoT sensor devices. At the lowest level in the system architecture are sensors and IoT sensor devices. Each animal has an individual IoT device with a set of different sensors. The sensor device is attached to the animal via a special collar. The test groups of sensors that model the information for experimental purposes are:

- acceleration sensor (measurement accuracy ± 0.1 g)
- angular deviation sensor (measurement accuracy ± 0.5°)
- special two-dimensional activity sensors (Fullamp1 and Fullamp2 sensors)
- localization sensor (measurement accuracy ± 10 meters).

Based on the angular deviation sensor, 6 virtual segmentation information distribution chains have been developed. Each has a large number of physical sensor measurements in a certain range for a time range (2 minutes). The angular deviation ranges are:

- -90°to -70°(Full9070 sensor);
- -69 °to -50 °(Full7050 sensor);
- -49°to -30°(Full5030 sensor);
- -29°to -10°(Full3010 sensor);
- -9°to 10°(Full1010 sensor);
- 11°to 90°(Full1090 sensor);

The angular deviation sensor generates a measurement result every half second.

The study includes two variants of IoT sensor devices that best meet the requirements:

Prototype 1 (Pr1) - Pr1 includes 8 types of activity sensors and GPS. Using GPS data from two consecutive transactions, the distance traveled in a straight line is calculated.

Prototype 2 (Pr2) - Pr2 is significantly simplified and includes only three activity sensors. Data from both sensor systems is acquired at a 2-minute interval.

The system concept, as well as the associated modules (hardware and software), are designed in a way that allows for the addition, modification, or removal of meta-sensors and sensor groups with minimal effort, which contributes to the flexibility of the research and meet the requirements of the subject area.

Figure 6. *Two prototypes of the created IoT devices*

The use of both types of devices/prototypes (Figure 6.), as well as the synthesis of their parameters, has the potential to generate a complete picture of the behavioral characteristics of individual animals, the herd habits of the group of observed animals, as well as collective herd behavior.

The next important step in optimizing the IoT device is to reduce some of the "intelligence" to the lowest level of sensors. Our tests showed that in order to obtain as much data as possible and to protect the correctness of the information received, it is necessary to collect more than 20 parameters every second (for example: GPS data, accelerometer, gyroscope, magnetometer, noise data, normalized position data, transmitter data, detector hardware parameters, etc.). Experimentally and analytically, we found that this approach provides the maximum amount of accurate information, but the critical point is the large amount of data that needs to be sent to the designed LoRa radio infrastructure. The amount of data, in turn, generates a number of problems in terms of energy optimization, regulatory European and global regulations that DO NOT allow exceeding the radio channel occupancy, and many others. Based on the needs of the measurements and the problems encountered, we came to the conclusion that it is necessary for the IoT device to collect and partially process the primary information. To minimize the information flow, partial processing of information, drawing intermediate conclusions and making certain decisions are implemented in the IoT device itself. The processed semi-normalized information is forwarded to the upper layers in the platform infrastructure model.

Transfer IoT sensor infrastructure. In parallel with the development of the IoT sensor devices of the cows, we also performed analyses and research in the field of transport and server environment of the overall project. Since pasture farming of animals requires receiving data from the static sensor network of the pastures, we created a formal model of the resulting IoT infrastructure [32] . This model presents the possibilities for overlapping the two sensor networks - the static sensor groups of the pasture and the dynamic sensor groups of the cows in this pasture. Let's consider the two sets:

– SGL = $\{sgl_1,\ldots,sgl_n\}$ as a set of IoT sensor groups included in the static sensor network of the pasture;
– SC = $\{sc_1,\ldots, sc_m\}$ as a set of dynamic IoT sensor devices placed on the cows in the herd;
– In addition, let's also consider sets:
– Date = $\{d_1,\ldots , d_k\}$ is a set of calendar dates on which measurements are performed, and
– Time = $\{t_1,\ldots , t_s\}$ is the set of time instants at which these measurements are performed;
– Location = $\{l_1,\ldots , l_n\}$ is a set of locations where the SGL sensor groups are installed.

We assume that each element of the two basic sets SGL and SC can include different types of sensors in the IoT device (for example, the two prototypes of sensors in cows), i.e. the elements of these sets will be represented as lists containing the values of the corresponding sensor measurement. Each sensor in the corresponding IoT has a permanent, pre-fixed position in the list. Sensors that do not participate in the corresponding group receive the value none in the list. Then the elements of the sets SGL and SC can be represented in the form:

– $sgl_i=(v_1,v_2,v_3,\ldots.v_p)$, where p is the number of all types of sensors in the pasture.
– $sc_i=(vc_1,vc_2,\ldots vc_k)$, where k is the number of different types of sensors in the cows' IoT devices.

Then we can define the combined virtual IoT sensor network as:

$$\boldsymbol{VSNET \subseteq (SGL \cup SC) \times Location \times Date \times Time}$$

The virtual network will be maintained in the virtual space at all infrastructure levels – in the server, in the Data Center and in the cloud. In the physical space, the two sensor networks exist independently of each other. The pasture communication network is used to transmit data to the next components of the platform. The developed infrastructure model considers the supporting static sensor IoT network of the pasture and the dynamic herd IoT sensor network, which is created when the herd enters the pasture (Fig. 7). The main transmission technology is the LoRa low-power wide-area network protocol, through which we were able to provide coverage over almost 10 quadrant kilometers with one central station, as well as a linear increase in range without limitations by adding additional stations (Fig. 8). Secondly, we used General Packet Radio Service (GPSR) communication. For the needs of the developed system, open frequencies for free use were selected as follows: 868Mhz for Europe and 433 for other countries with different regulations. The frequency range complies with local government radio broadcasting regulations. The frequencies on which we use the second GPRS technology are 850/900/1800/1900MHz.

The use of a unified transmission medium for both types of sensors allows for optimized transmission and processing of information. Depending on the specific environmental settings, the proposed infrastructure can achieve transmission parameters of over 10 km from the central station and over two years of autonomous operation of animal sensors and over six years of autonomous operation of static pasture sensors.

Virtual Operations Center. Modeling and information processing. The main module in the system is the Virtual Operations Center (VOC). It extends and complements the basic ViPS architecture with components dependent on the researched subject area and includes the software and presentation layers of the infrastructure model [32].

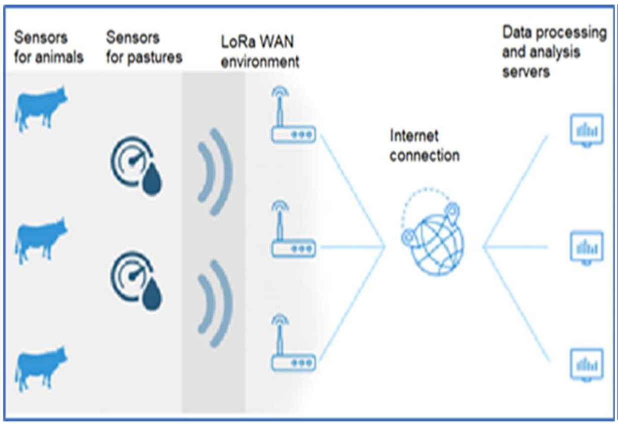

Figure 7. *Building the IoT infrastructure*

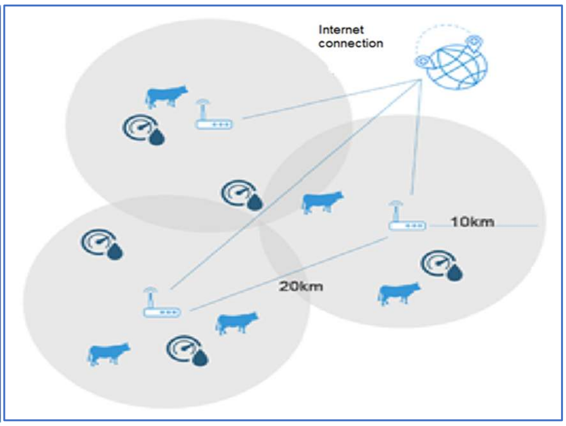

Figure 8. *Broad-based infrastructure model*

The first prototype of VOC includes the following five main components: sensor management component; device management component; farm management component; device calibration component and data converters. **The sensor management component** provides the functionalities for adding, modifying and removing information from sensors. This includes complete information about the data that the sensor provides, as well as the meta information necessary for its identification. **The device management component** provides the functionality for adding, modifying and removing virtual IoT devices (sensor groups). Virtual devices present in the virtual world information about real physical devices and include complete information about the sensors that compose them, without limitation of their type and number. **The farm management component** provides functionalities for managing a farm with their grazing animals and devices operating on its territory. This component provides: adding, modifying and removing a farm; determining the location of the farm and the territory on which it is located; adding, changing and removing cattle on the farm; activating/deactivating a device for an animal or a specific location within the pasture. **The device calibration component** aims to change the device settings by tracking animal behavior. **The data converter** converts the received semi-normalized data into a form suitable for storage and processing.

After a period of testing and analysis, the VOC architecture was supplemented with several more components. The architecture of **the second VOC prototype** [33], [35] is presented in the following figure 9.

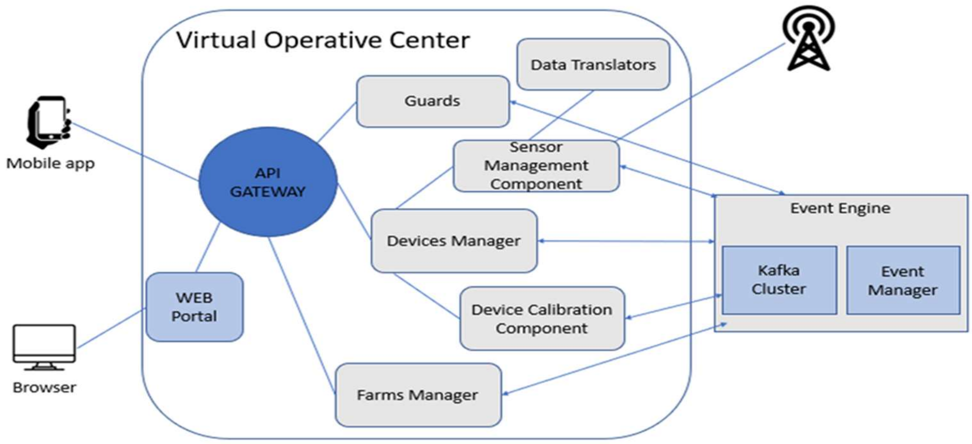

Figure 9. *Architecture of the current prototype of the Virtual Operations Center*

The Farm Manager component provides the ability to provide various types of services related to animals and farm management. Animal management includes animal health services, pedigrees, medical records, etc. Farm management services include pasture management, etc. **The Device Manager** provides a set of functionalities for declaring different device configurations with a specific set of sensors. Device registration requires a relationship with a given configuration, previously defined in the provided services. The component also provides services for activating a device that requires a connection to a specific animal or pasture coordinates on the farm (Figure 10).

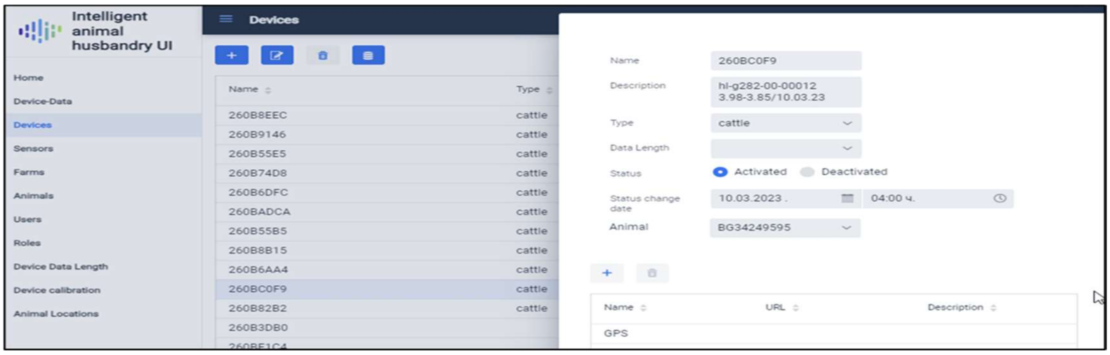

Figure 5*Device Manager in VOC*

The sensor management component is designed to register and manage information from sensors, and **the device calibration component** is used to calibrate the results. In order to monitor animal behavior, it is necessary to categorize the data collected by the devices based on a given template. For each type of device, it is necessary to develop a specific calibration template. The process of creating, storing and applying the templates is managed by the device calibration component. Calibration involves monitoring animal behavior both through the devices and through direct observation by specialists in the field of animal husbandry (zooengineers). In the process of receiving data from the devices, the data is linked to the result of direct observation. Subsequently, by applying statistical analysis of the overall information, the specific template is created for the needs of future optimizations and analyses. The **Data Translators** component is responsible for normalizing the semi-normalized data provided by the devices, **the Guard component** provides a set of services related to the safety of animal units, such as: leaving the pasture perimeter, immobility for a certain period, separation from the herd, etc.

Only registered users have access to the application, and the various functionalities are only available to users with the necessary rights:

– Users with the "Sensor Administrator" role have access to sensor management features.
– Users with the device administrator role have access to the device management screens.
– Users with the "farm administrator" role have access to farm and animal information management screens.
– Users marked as farm managers and those with the "farm administrator" role have access to the device data screens.

The sensor administrator has full access to the sensor management functions. He gets a visualization of the available sensors with the ability to filter and sort. Above the table are the buttons for adding, changing and deleting a sensor. The buttons for changing and deleting are activated when selecting or writing to the table. When you select the "Add" or "Change" button, a dialog box opens with detailed information about the sensor. Three fields are available: name - sensor identifier; description - sensor description; URL - link to a page with additional information about the sensor.

Each sensor provides data from its operation in some form. For this reason, there is a table in the dialog where (with the buttons above it) information about the sensor data can be added. The order of the entries in the sensor data table is important. Users with a *device administrator profile* have access to the device management functions. The screen consists of a table with available devices and options for adding a new device, changing a device, and deleting devices. When an IoT sensor device is activated, the system receives information about its location, which is visualized on the pasture map. In the process of developing and testing the prototypes, we focused on **three types of pastures** for environmentally friendly cow farming:

– Cow farm and pasture at the Experimental Farm of the Agricultural University-Plovdiv (AU).
– A mountain farm and pasture with difficult-to-access terrain near the town of Momchilgrad (in the southeastern part of the Rhodope Mountains).
– A farm and pasture along the Danube River with specific features – a border area with no or insufficient internet and mobile connectivity; flat terrain with steep banks towards the river.

Currently, studies are being conducted related to the stability of the connection of sensor devices with the Virtual Operations Center (VOC). In this regard, parallel experiments are being conducted in the other two farms, with beef and local breeds of cows. One farm is located in a mountainous semi-crossed terrain (Figure 11), and the other is along the Danube River - with steep banks of the river (Figure 12). The animals on both farms spend most of the year on pastures, distant from the farms, which is why it is impossible to use WiFi. Also, along the Danube River, due to the steep banks and the close border with Romania, there is no coverage of Bulgarian mobile operators.

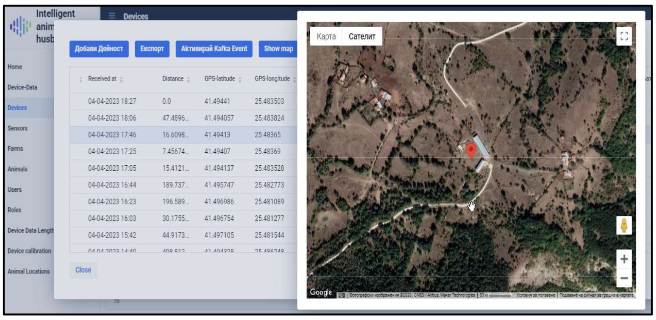

Figure 11. VOC information processing for animals in a high mountain pasture

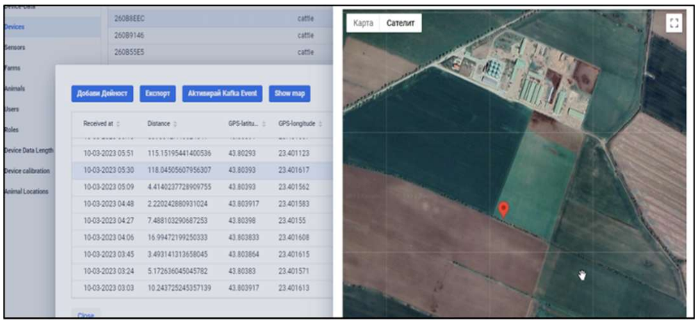

Figure 6. VOC information processing for the animals in the Danube River region

The data goes through several levels of cleaning and transformation before being processed in VOC. All interested users have access to them at different levels, according to their rights. For example, the *sensor table* visualizes the sensors that are included in the IoT device (Fig.13).

Device-Data

Device Idetifier	Channel Rssi	Row Data	Gps Latitude	Gps Longitude	Device Temperature	Received At	Ax
260BEC86	-33	ff9a2842e40cc641480...	42.151363	24.756294	27.529999	2021-08-04T11:55:59...	72
260BEC86	-35	ff9a2842e30cc641c00...	42.151363	24.756292	27.529999	2021-08-03T11:41:23...	448
260BEC86	-32	ff9a2842e20cc641200...	42.151363	24.75629	26.529999	2021-07-28T06:52:41...	288
260BEC86	-31	ff9a2842d60cc641b00...	42.151363	24.756268	28.529999	2021-08-05T14:53:32...	176

Figure 7. *Managing sensor data in an IoT device*

IoT device is activated, it starts sending semi-normalized data, which is further processed and data for the IoT device with a specific configuration is visualized on the screen. Users with the role of "Farm Administrator" receive data from all devices, while users marked as farm managers/owners see only data from devices activated in their farm.

The second version of VOC includes an updated version of the data presentation. The first version of the calibration component (Fig. 14) has also been implemented. The component provides two approaches to presenting the data from the device and the current activity of the animal. In the first approach, the user manually selects a record and adds the necessary information (Figure 15).

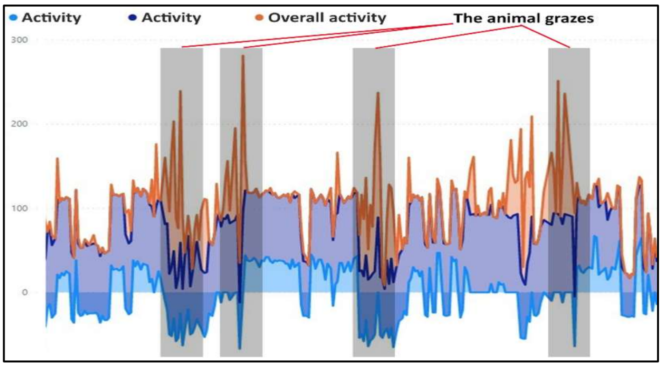

Figure 14. *Calibration component data*

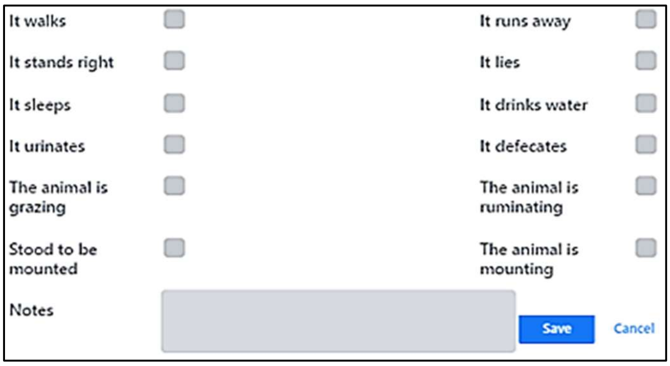

Figure 15. *User perspective on the activity of the cows*

The second approach is proactive, based on Kafka Streams. The Calibration component provides a listener and when activated, the component will automatically show the user the view of animal activity. The provided data is linked to the device data and can be analyzed in the next step of the calibration. The output of the calibration process are models of representation of sensor data for each animal activity. These models will be used to process the data from the IoT device and the user (farmer) can receive information about the current activity of the animal. In the next version of the Calibration component, an approach to automate the creation of these models will be implemented.

2. Analysis of primary results and data testing

in **Prototype 1.** Geolocation uses a GPS sensor that positions the animal and measures the distance traveled per unit of time, as well as performing various types of behavioral analyses in relation to grazing areas. We also use sensors to position the animal's neck by acting on 3 spatial planes. The data allows us to measure in detail the overall behavior of the animal by determining the position of the head. In combination with the other data, we aim to create a complete behavior model. The third group of sensors is a combination of several two-dimensional activity sensors. They allow the completion of the entire data set and the digital expression of the behavior and activity of the animal. The set of three main groups of sensors is analyzed and combined primarily at the sensor level, which is subsequently processed in detail in the software layer. Sensor data is collected at 2-minute intervals. Physical observation (by zoo engineers) was also performed to calibrate the behavior of the animals against the incoming sensor data. With each transaction of data from the sensors, through the relevant functionality of the system, a request is generated to the observer to enter a specific activity at the time of receiving the data. The system allows the observer to select several activities simultaneously. The connection of the real activities of the animals with the relevant sensor data serves to check and verify the developed model. The physically observed and reported reactions of the animals for the individual types of devices are as follows:

- for Prototype 1 – 265 observations
- for Prototype 2 – 314 observations.

The prototype software used to calibrate and control the sensors has options for activities such as: walking; rumination; sleeping; grazing; running; lying down; standing up, etc. The observer is prompted by the calibration component to select one or more of the activities that the animal has performed during the previous two-minute period. Due to the short period of physical observation of behavior, insufficient data was collected for some of the activities to be included in the statistical analysis.

In order to analyze the relationship between the data from the device and the actual behavioral responses at a given time, **a multivariate** linear model (1) is used, through which we take into account the influence of activity as a factor on the data obtained from each of the sensors. The statistical model is used separately to analyze the data of each of the prototypes.

$$Yij=\mu+Di+eij, (1)$$

Where: Yij is an observation vector (activity that the animal performs); μ is a common mean constant; Di is the fixed effect of the ith action (**Prototype 1** : walking, running, grazing, grazing and searching for pasture grass, grazing on leaves of woody vegetation; **Prototype 2-** fighting, walking, climbing, lying, lying and experiencing, grazing, standing up and standing up and experiencing); eij is the residual variance.

Table 1. *Statistical processing of data from the two prototypes*

Prototype devices	Sensors	F	Sig.
Prototype 1	Fullamp2, rad/T	2.01	0.098
	Fullamp1, rad/T	52.3	0.000
	Full9070, N/T	2.19	0.075
	Full7050, N/T	5.50	0.000
	Full5030, N/T	5.15	0.001
	Full3010, N/T	5.03	0.001
	Full1010, N/T	12.4	0.000
	Full1090, N/T	10.1	0.000
	Distance, m	75.4	0.000
Prototype 2	Activity , Hz/T	11.3	0.000
	axX	43.1	0.000
	axY	20.9	0.000

Table 1 shows that the activity performed at the time of receiving the data from the sensors significantly affects most of the device values. Only two of the twelve sensors used - Fullamp2 (activity sensor) and Full9070 (accelerometer), located in Prototype 1, for which we have significantly less data, had a minor impact. These results give us reason to assume that with the accumulation of a sufficiently large array of data collected in parallel by the sensors and visual recording of the animal's activity, we can successfully use multivariate analysis of variance as a statistical tool for checking the adequacy of the sensors included in the devices for tracking animal behavior. The 2-minute period in which the data from the sensors are received is quite sufficient to perform system calibration.

Table 2 presents the results of the study conducted on prototype 1. It shows that for each activity the mean values of the sensor data differ significantly. On the other hand, a unique combination of indicators can be observed for the different activities. For example, the activities “Grazing” and “Grazing and foraging” seem close, but it is noticeable that the distance reported based on the GPS sensor differs significantly – 27.01 ± 2.662 m and 35.62 ± 6.137 m, respectively (P <0.001). More significant differences in these two activities are also observed between the indicators of Fullamp1.

Sensor	Walking		Running		Pasha		Grazing and searching for pasture grass		Grazing on leaves of woody vegetation	
Sensor	Mean	± SE	Mean	± SE	Mean	± SE	Mea n	± SE	Mean	SE
Fullamp2 [1] , rad/T	232.0	4.66	158	99.9	238.8	10.8	185.2	5.0	132.5	49.9
Fullamp1 [1] , rad/T	56.0	9.27	296	20.7	18.6	2.25	26.9	5.18	70.3	10.4
Full9070 [2] , N/A	8.00	3.21	2.00	7.17	12.8	0.78	11.2	1.79	4.75	3.59

Full7050 ², N/T	37.8	8.77	3.00	19.6	52.8	2.13	56.7	4.90	17.0	9.80
Full5030 ², N/T	27.4	5.39	6.00	12.0	37.6	1.31	34.6	3.01	16.7	6.02
Full3010 ², N/T	25.0	4.06	39.0	9.08	11.6	0.98	10.2	2.27	14.7	4.54
Full1010 ², N/T	12.4	2.94	35.0	6.57	5.14	0.712	7.37	1.64	22.2	3.28
Full1090 ², N/T	12.2	7.40	41.0	16.5	5.75	1.79	5.62	4.14	56.5	8.27
Distance, m	57.4	11.0	452.2	24.5	27.0	2.66	35.6	6.137	38.7	12.3

***Table 2. Average** values of data obtained from prototype 1.*

([1] Number of measurements in a given angular range/time period 2 minutes; [2] radians/time period 2 min
SE = standard error)

Two of the sensors used, Fullamp2 and Full9070, have high impedance and high statistical error due to insufficient data collected from physical behavioral observations. In this regard, it is necessary to conduct a larger number of physical observations to cover more activities and determine statistical intervals of variation for each sensor.

Prototype 2 includes three sensors: an activity sensor; an acceleration sensor; and an angular displacement sensor along the X and Y axes. Despite the small number of sensors, compared to their high productivity and data comparison, it is clear that they provide sufficiently reliable information for a clear differentiation of different types of activities. With this prototype, we were able to collect a larger volume of data for more types of activities, with all activities differing significantly and being statistically significant ($P<0.001$). Based on Umstätter et al. (2008) [35] **Error! Reference source not found.**, we assume that accelerometers can reliably distinguish between lying and standing positions of animals. This is crucial for monitoring the cow, as excessive lying time can indicate health problems (Fig. 16).

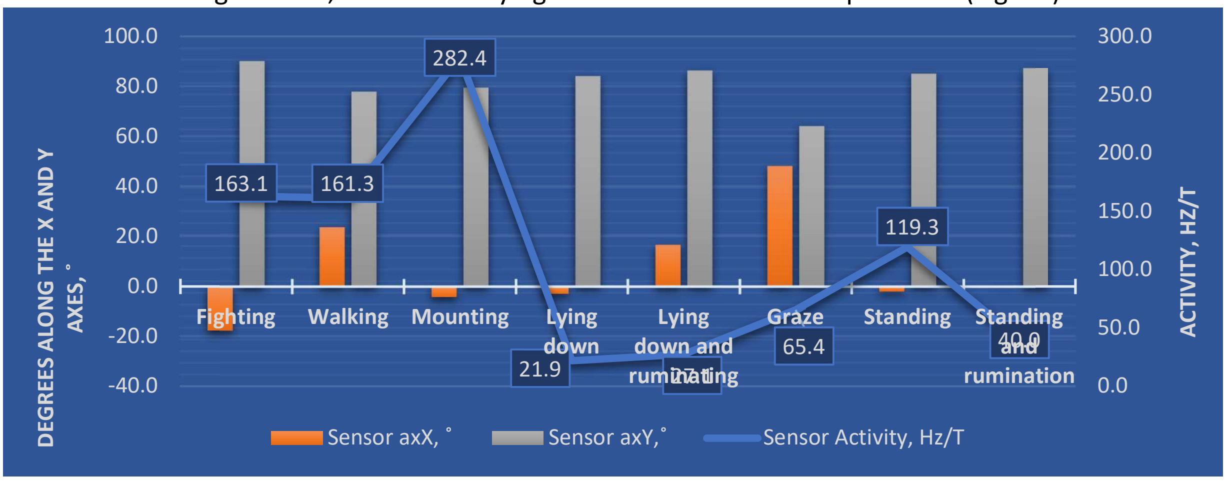

***Figure 16.** Influence of activities on sensor performance (Prototype 2)*

The largest differences for all activities are observed in terms of the activity sensor groups. The deviation along X is in the negative scale of values, most significantly for "jumping" and "quarrels between animals". For walking, lying and experiencing, as well as for grazing, the deviation along X has positive values. For all other activities, the values are close to zero. Since the devices for Prototype 2 are equipped with a weight placed at the lower end of the collar, the gyroscope hardly changes its position along Y, respectively, the Y measurements for all activities have very close values – from 64.2 ± 1.45 to 90.2 ± 4.70 ($P<0.001$). Similar to Prototype 1, each activity is characterized by a unique combination of average values from the data from all sensors. With subsequent software determination and processing of the limits of variation of each indicator for the respective activity and the specific combination of all of them, it would allow us to successfully differentiate and recognize the respective activity. This will allow data from the developed system to come in the form of activities, such as time spent grazing, resting, walking, etc. all characteristics of the animal's behavior by which to assess its well-being and indirectly the lack or presence of sufficient pasture grass.

Correlations between different activities and sensors:

– Grazing (Pr1) correlated strongly with head tilt (Full3010, Full1010, Full7050).
– Walking and running (Pr1) are directly dependent on GPS and Fullamp1.
– Jumping and fighting (Pr2) – most distinct through axX and Activity Hz/T.
– Lying and ruminating (Pr2) – low Activity Hz/T values, stable axY.

Therefore:

– Prototype 1 is more accurate for recognizing grazing and static activities, but some sensors do not provide enough data (Full9070, Fullamp2).

– Prototype 2 successfully differentiates dynamic activities such as fighting and jumping but is less sensitive to different head positions.
– The best model would be a combination of the Pr1 and Pr2 sensors.

3. Future plans and directions for research on the topic

Future plans for the development of the IoT platform, as a specific adaptation of the reference ViPS architecture, include the development of personal assistants for the various participants - farmers, zoo engineers, veterinary specialists, administrators, etc. The sensors transmit data to the central data receiving devices, and the intelligent layers process and analyze the information based on the location of the livestock relative to the location of the regulated pastures on which the animals were fed. The data center should ensure the intelligent functioning of the system. In this component, a virtual "combination" of the two types of sensor networks was performed, and the data can be used to develop two types of models: a pasture model, which represents the current state of the pasture itself as the development of the grass stand, and a physiological model, which represents the physiological state of the animals that grazed on this pasture.

The processed data can be the basis for developing economic models that will allow for the preparation of analyses and forecasts such as "How does the quality and volume of production (meat, milk, cheese, etc.) depend on the reported parameters of pastures and the physiological characteristics of animals?" In the future, the construction of a "Smart Pastures (Meadows)" blockchain may be considered.

Multivariate analysis of variance can be successfully applied as a statistical tool for checking the adequacy of sensors included in animal behavior tracking devices. In addition, it can be used to determine reference values and combinations of sensor data to account for the activity-behavior patterns of each animal. The results give us reason to assume that with the accumulation of a sufficiently large array of data collected in parallel by sensors and visual reporting of the animal's activity, we can successfully use multivariate analysis as a statistical tool for checking the adequacy of sensors included in animal behavior tracking devices. In the future, with subsequent software determination of the limits of variation of each indicator for the respective activity and the specific combination of all of them, it would allow us to successfully distinguish and recognize the respective activity. This will allow the data from the developed system to come in the form of activities, such as time spent grazing, resting, walking, etc. all the behavioral characteristics of the animal, by which its welfare can be assessed and indirectly the lack or presence of sufficient pasture grass.

Another direction for future research is the use of AI approaches and machine learning algorithms. Intelligent components using ML algorithms can be deployed in VOC, which, in addition to predicting animal behavior, can help determine the condition and qualities of the grassland. In addition, they can solve tasks such as: identifying poisonous and harmful plants for animals, recognizing rare and protected plants, etc. In addition, various optimization tasks can be solved in VOC, such as determining the load on pastures and the optimal number of animals that can feed for one growing season for one pasture depending on its current condition. This gives reason to define as a goal for future development of the system the creation of a specialized analysis and optimization module using DRL and other AI algorithms as part of the Analytical Subspace of the reference ViPS architecture.

4. Conclusions from Chapter Three

1. The created sensor network and IoT devices meet the requirements of the task of ensuring sustainable receipt, pre-processing and transmission of semi-normalized information, as well as achieving energy efficiency.
2. The latest version of the Virtual Operations Center provides a convenient environment for processing, analyzing and visualizing information about animal behavior and activities. It is necessary to continue research into the development of personal assistants to ensure effective communication between farmers and the system.
3. Statistical processing of information provides a good basis for continuing research aimed at creating sustainable behavioral models of pasture-raised cows. It is necessary to continue working on the application of AI algorithms to predict and optimize herd behavior of animals.

CONCLUSION

The dissertation presents a study on the concept creation, modeling and prototyping of an IoT environment for intelligent livestock farming. An architectural framework of additional modules has been developed to complement the basic reference ViPS architecture in the field of intelligent pasture livestock farming. The development of two basic prototypes of these modules is presented and the results of the study of the behavioral patterns of cows raised freely on remote pastures, through the dynamically received information from the IoT platform, are discussed. Plans for future research are outlined and some conceptual models for the development of additional components for predicting and managing the movement and herd behavior of animals using AI algorithms are shared.

Main tasks solved in the dissertation research

1. The need and possibilities for building an IoT ecosystem in the field of intelligent animal husbandry in the context of pasture cattle breeding have been studied;
2. An appropriate software architecture for the platform has been developed;
3. Sensor devices have been developed and two prototypes of a software and hardware IoT platform for smart pasture cattle breeding have been created.
4. An approach is proposed for processing and analyzing the obtained data to study the behavior of cows during pasture farming in the created prototypes.

Results of the scientific study

In carrying out the tasks to achieve the main goals, we can determine the following current results (contributions) from the scientific research:

1. A general concept has been created for building an IoT ecosystem in the field of smart animal husbandry.
2. Specific models have been created for the application of the developed concept in the adaptation of the reference ViPS architecture in the field of intelligent pasture animal husbandry.
3. Prototypes have been created to test the application of the designed IoT environment for intelligent animal husbandry.
4. is proposed for processing and analyzing the obtained data to study the behavior of cows during pasture farming in the created prototypes.

The relationship between the results, tasks, structure of the dissertation and the publications involved in the procedure are presented in the following table.

Task	Result / Contribution	Chapter	Publications
1	1	1	1, 2
2	2	1, 2, 3	1, 2
3	3	2, 3	1, 2
4	3.4	2,3,4	1 , 2

Approbations

Participation in projects:

Project "Digital Sustainable Ecosystems - Technological Solutions and Social Models for Ecosystem Sustainability (DUEkoS) - BG-RRP-2.004-0001-C01, as a researcher in 2023.

Reports at scientific conferences:

1. International Conference "International Conference Automatics and Informatics (ICAI), Varna, Bulgaria, October 1-3, 2021, with a report " INFRASTRUCTURE MODEL OF INTELLIGENT PASTURE „.
2. International Conference "Big Data, Knowledge and Control Systems Engineering (BdKCSE)“, Varna, November 2021 with a report " MODELIZATION OF A SYSTEM FOR INTELLIGENT ANIMAL HUSBANDRY"
3. International conference 7th IFAC Conference on Sensing, Control and Automation Technologies for Agriculture, 14-16 September 2022, Munich, Germany with report " APPROACH FOR MODELING AND IMPLEMENTATION OF AN INTELLIGENT SYSTEM FOR LIVESTOCK CATTLE ON PASTURES „.
4. International Conference "Informatics, Mathematics, Education and Their Applications (IMEA'2024)", Pamporovo, November 13-15, 2024, with a report "AN INFRASTRUCTURE APPROACH TO BUILDING AN IOT ECOSYSTEM FOR AGRICULTURE"
5. Participation in regular scientific seminars organized by the Institute of Information and Communication Technologies of the Bulgarian Academy of Sciences for the work on the national program "Smart Agriculture" with reports on the current status of the IoT platform for smart animal husbandry.

PUBLICATIONS ON THE DISSERTATION

1. Valchev, E., Todorov, J., Stoyanov, I., Monov, V., Dimitrov B., and L. Doukovska, "Infrastructure Model of Intelligent Pasture," 2021 International Conference Automatics and Informatics (ICAI), Varna, Bulgaria, 2021, pp. 318-321, doi: 10.1109/ICAI52893.2021.9639655. (SCOPUS)

2. Valchev, E., Malinov, P., Glushkova, T., Nikolov, V., Doukovska L. and V. Monov, "Modeling of a system for intelligent animal husbandry," 2021 Big Data, Knowledge and Control Systems Engineering (BdKCSE), 2021, pp. 1-8, doi: 10.1109/BdKCSE53180.2021.9627312. ISBN:978-1-6654-1042- 7 (SCOPUS)

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