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ORIGINAL ARTICLE

The future of human and animal digital health platforms

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Abstract

Electronic Health (eHealth) has emerged as a pivotal driver of change in modern healthcare, reshaping the way medical information is collected, processed, and utilized. e-health includes digital solutions aimed at improving healthcare delivery, management, and accessibility. The Internet of Medical Things (IoMT) is specifically focused on establishing connections between medical devices and sensors to gather and transmit health-related data. Its primary objective is to enhance healthcare by facilitating real-time monitoring, employing data analytics, and integrating intelligent medical devices. The IoMT and, more broadly, eHealth are yielding positive outcomes, prompting their expanding application into the animal domain. Recent technological advancements facilitate the integration of health platforms, fostering a connection between human and animal health for improved well-being. This article introduces a conceptual framework that synthesizes the main activities in the medial data acquisition-processing pipeline. The framework has been derived from an analysis of the state of the art in the field of the IoMT in human healthcare. Furthermore, the article explores the application of eHealth concepts in the animal domain. Addressing both human and animal health, the paper summarizes the outstanding issues that need to be addressed for the full integration of these technologies into daily life.

Keywords IoMT · Platform · Human health · Animal health · eHealth · Veterinary

1 Introduction

The ever-increasing interconnection of medical devices and systems, and the significant technological advancements, are substantially transforming the way medical care is delivered. These advances improve the overall efficiency of healthcare systems, thus promoting individuals' well-being in alignment with the goals of Society 5.0 [1]. Modern solutions are not confined to human health alone but extend their scope to animal health, marking a significant change towards a more integrated health ecosystem. The emerging technologies offer new opportunities for improved monitoring, precise diagnosis, and predictive analysis, all of which hold paramount significance within healthcare platforms, encompassing both human and animal domains. The increasing integration of Artificial Intelligence (AI) plays a pivotal role in advancing the healthcare sector towards a phase where decisions grounded in data can augment the quality of care extended to both human patients and animals. These technological advancements contribute to the promotion of more effective and informed healthcare practices across species.

As health platforms evolve, the lines between human and animal health are blurring, creating the way for a more integrated approaches to innovative health platforms via cross-industry innovations. This shift emphasizes the need for a comprehensive analysis of current implementations, ongoing research, and the challenges faced by both domains. In this paper, we aim to explore some selected relevant work on the future landscape of smart health platforms, focusing on both human and animal health sectors. We examine the existing work and challenges, delve into the latest research, and identify the challenges hindering the smooth operation and integration of these platforms.

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This article presents a detailed analysis, dedicating separate sections to human and animal health platforms as they differ significantly in maturity, focus, and challenges.

The section on human health platforms introduces a conceptual framework to serve a dual purpose. On one hand, it functions as a precise mapping tool for research outcomes, facilitating a nuanced understanding of the study's results. On the other hand, it serves as a mechanism for distinctively delineating the responsibilities that medical data acquisition and processing systems must separate. This clear demarcation aims to ensure both evolutionary adaptability and seamless integration within the broader healthcare infrastructure. This conceptual framework originates from an in-depth analysis of the state of the art in Internet of Medical Things (IoMT) platforms, a pivotal element supporting the foundation of eHealth.

Similarly, the discussion on animal health platforms covers the emerging ecosystem of veterinary platforms, the early but promising field of remote veterinary diagnostics powered, the untapped potential of animal wearables, and the need for establishing global standards. Both sections conclude by synthesizing the challenges and thus suggesting promising research directions.

Lastly, given the maturity of eHealth technologies in the human domain, a section is dedicated to describing the open issues and challenges that must be addressed to transfer some of the findings from human eHealth to the realm of animal healthcare. The integration of eHealth technologies in the animal domain presents multifaceted challenges, spanning diverse species, data security, technological design, and interoperability. Overcoming these hurdles requires collaborative efforts across disciplines, involving technology professionals, veterinarians, and farmers. Innovative solutions and standardized practices are crucial to ensuring the effective and sustainable implementation of eHealth for the mutual benefit of humans and animals.

The structure of the paper is as follows. Section 2 addresses digital healthcare for humans, with a specific focus on IoMT solutions. The section starts by outlining the typical architecture of IoMT platforms, followed by an analysis of existing solutions, providing an overview of current directions. Lastly, the section offers insights into the open challenges, which currently demand the attention and efforts of researchers. Section 3 focuses on the animal health platforms, starting with a focused state of the art analysis with regards to upcoming applications. Furthermore, an overview of the challenges in animal health platforms is given, followed by technical directions derived from the analysis to make animal health platforms ready for future applications and innovations. Section 4 discusses challenges in applying eHealth technologies in the animal domain. Finally, Sect. 5 provides final remarks.

2 Human health platforms

The seamless integration of digital technologies and medical services has led to *eHealth*, a paradigm shift that significantly changes the delivery of health care and the management and participation of patients on the care pathway. eHealth involves the use of digital technologies such as computers, the Internet, and mobile devices to enhance health services and information delivery [2]. eHealth is built on a patient-centric vision, with the aim of providing efficient and personalized care pathways through the use of digital technological solutions. The principles underlying eHealth offer a variety of opportunities, including overcoming geographical boundaries, patient engagement and awareness, personalized treatment, early detection of ongoing pathologies, and the management of chronic diseases.

Central to this paradigm shift are *digital health platform*s, ecosystems that leverage digital technologies (e.g., electronic data, devices, software solutions) to enhance the efficiency, accessibility, and quality of healthcare services.

Among the digital health platforms, IoMT emerges as a pivotal platform that leverages the interconnection of medical devices and systems by integrating them into a comprehensive network to improve patient care, healthcare efficiency, and clinical outcomes [3].

IoMT platforms serve multiple functions in eHealth. They enable *real-time data collection* by seamlessly gathering patient information from various devices. Real-time data collection enables *early detection of anomalies* facilitating timely interventions to prevent complications. *Personalized treatments* are crafted on the basis of patient-specific data. *Remote care* reduces the necessity for frequent in-person visits, particularly beneficial for those with chronic conditions and individuals in remote areas. *Interoperability and standardization* promote seamless data exchange across devices and healthcare systems, facilitating data integration and analysis within electronic health records and clinical decision support systems. IoMT empowers proactive healthcare, fostering a *patient-centric* healthcare approach: patients actively engage in their healthcare management by accessing their health data, making informed decisions, and taking steps to proactively maintain their well-being. Finally, IoMT is particularly effective in *long-term chronic disease management*, enabling continuous monitoring of vital signs, medication adherence, and lifestyle factors. This characteristic supports timely interventions, decreases hospital readmissions, and ultimately improves the quality of life of patients with chronic diseases.

Section 2.1 outlines the common-shared architecture of IoMT systems, Sect. 2.2 introduces some IoMT solutions, and Sect. 2.3 addresses the current open challenges that research is focusing on.

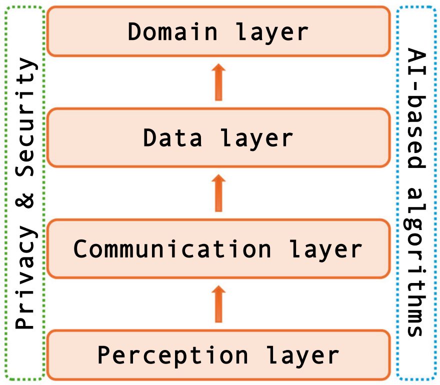


Fig. 1 IoMT architecture

2.1 Architecture of IoMT systems

IoMT systems are distinguished by their layered architectural solutions. However, there is no one-size-fits-all architecture, as it varies depending on factors like the intended purpose of the system. Even when functional requirements are similar, unique constraints such as specific clinical needs, available connectivity infrastructure, security and privacy requirements, and more can influence the design. For example, two IoMT systems designed for remote patient monitoring. Although both share the core function of collecting patient data and transmitting it to healthcare providers, their architectures may differ due to factors such as the specific medical conditions they address, the level of patient participation, or the existing network infrastructure in the regions where they are deployed.

Regardless of the specific monitoring requirements, all systems adhere to a unified architectural design sketched in Fig. 1. Several proposals in the literature (e.g., the one by Dwivedi et al. [4]) align with the general framework, albeit with potential variations in the number of layers compared to those depicted in Fig. 1. Layers provides a clear allocation of responsibilities. It is noteworthy that there is some flexibility in grouping different responsibilities within a single layer.

The *Perception* (or *Sensing*) layer encompasses smart objects, medical devices, a variety of sensors, and any other kind of physical device capable of detecting environmental and physiological data, including devices aimed at acquiring data for patient health monitoring.

Among the sensors employed, those for blood pressure measurement emerge as critical components for continuous monitoring of cardiovascular conditions. Glucose sensors help in diabetes management, offering continuous monitoring of blood glucose levels. Body temperature, monitored through digital and infrared thermometers, is a clear indicator of health condition. Pulse oximeters register the oxygen saturation level (SpO2) in a person's blood, particularly relevant for those who suffer from pulmonary disease. Electroencephalography (EEG) sensors are used to detect and record electrical activity of the brain, facilitating the diagnosis of conditions such as epilepsy, sleep disorders, brain injuries, and various neurological conditions.

In addition to specialized medical devices, smartwatches and smartphones are widely used in this context due to their widespread adoption and versatility. These devices are equipped with a wide range of sensors, the data of which can be collected in a manner similar to that of medical devices. Furthermore, the manufacturers of these devices provide aggregated information on the patient's quality of life, offering support in diagnoses, such as sleep quality, step count, and more. In summary, the perception layer in IoMT utilizes a wide array of sensors, each contributing significantly to personalized and continuous monitoring of patient health. The survey by Osama et al. [5] presents an up-to-date list of both medical and non-medical devices employed within the perception (or sensing) layer.

The *Communication* layer assumes the responsibility of establishing sensor connectivity, thereby facilitating the aggregation of data from diverse devices within the perception layer regardless of their underlying technologies or protocols. Thus, the communication layer serves as an intermediary, functioning as a bridge and interpreter that facilitates effective inter-machine communication within complex and heterogeneous technological frameworks.

Relying on industry standards and best practices within the communication layer is fundamental. By adhering to established norms, this layer creates a cohesive environment where different systems can interact with agility and security. This adherence to standards not only streamlines the communication process, but also ensures that it transpires swiftly and with a high level of security, mitigating the risks associated with unauthorized access and potential vulnerabilities.

As highlighted by Mrinai et al. [6], several factors influence the choice of transmission technologies (ISO/OSI network layer) and protocols (ISO/OSI application layer): characteristics of specific devices, the chosen computing architecture and deployment strategy, nature of the application, the need for real-time data, bandwidth constraints, and compatibility with the broader network infrastructure. Commonly used network-layer protocols in IoMT systems include Bluetooth, BLE, Zigbee, Wi-Fi, and 3G/4G/5G. Concerning the application layer, the protocols used are partly derived from Internet of Things (IoT) systems and include Queue Telemetry Transport protocol (MQTT), HTTP/HTTPS, and Constrained Application Protocol (CoAP) [7].

Within the communication layer, two prominent standards emerge: IEEE 11073 [8] and HL7/FHIR [9]. IEEE 11073, also known as the IEEE Standard for Health Informatics—Personal Health Device Communication, is a widely recognized standard that facilitates interoperability among personal health devices and health information systems. It establishes a framework for communication protocols, data formats, and device semantics, ensuring seamless integration and communication between various medical devices and healthcare systems. This standard plays a crucial role in enabling the exchange of health data, such as vital signs, medical measurements, and patient information, in a standardized and interoperable manner. HL7/FHIR (Health Level Seven/Fast Healthcare Interoperability Resources) is another standard in the realm of healthcare informatics. FHIR is a standard designed to support exchanging clinical data across different healthcare systems and applications.

Varying data transmission methods and data format disparities create significant challenges for the seamless integration of data sources in IoMT solutions [10].

The *Data layer* manages and processes a huge amounts of data generated by medical devices and sensors. This layer can be logically divided into two sub-layers according to their responsibilities. The *Edge* sub-layer involves on-site processing and immediate data analysis near the point of data origin. Conversely, the *Cloud* sub-layer encompasses centralized infrastructure for long-term storage, in-depth data analytics, and advanced processing.

The *Edge* layer is optional but highly recommended. In fact, its primary role in an IoMT ecosystem is to decentralize processing tasks from the cloud, enabling real-time decision-making for time-sensitive applications, such as patient remote monitoring. This on-edge processing includes data cleaning and filtering to reduce data transport costs, minimize bandwidth requirements, establish secure channels between the perception and cloud layers, and to adopt an environmentally conscious computation approach [11].

As in traditional IoT systems, between the edge and the cloud, an additional layer known as *Fog* may exist. While edge-level processing occurs locally in close proximity to the acquisition devices (perception layer), the fog-level processing aggregates computations from multiple interconnected edges nodes. The fog layer serves as an intermediary to optimize data processing, enhance real-time capabilities, and improve overall efficiency in IoMT systems [12].

The *Cloud* layer serves as a crucial component in securely storing and organizing healthcare data, facilitating efficient analysis, and enabling streamlined retrieval for further examination. In the eHealth domain, private and community clouds are typically employed, as applications and services deal with sensitive patient information and medical data [7].

An interesting analysis of how the edge and cloud computing paradigms enhance performance, availability, and reliability in IoMT environments can be fount in [12].

Finally, the *Domain Layer* is responsible for analyzing and interpreting data and delivering of application-specific services.

Cross-cutting the data flow of a IoMT ecosystem, significant factors come into play, precisely, data *privacy and security* and *artificial intelligence-based* techniques that allow insights to be gleaned from the acquired data.

Medical data is sensitive. Transmitting and storing patients' personal information through Internet-connected devices increases the risk of unauthorized access. Cybersecurity threats, such as ransomware attacks or data breaches, require a stringent implementation of advanced security protocols, robust encryption, and constant updates to protect the integrity of health data.

Blockchain technology presents a compelling solution to privacy and security issues in the healthcare domain [13, 14]. Its decentralized and tamper-resistant framework ensures that medical records are securely stored across a network of nodes, reducing the risk of a single point of failure. Through smart contracts, patients gain control over data access, fostering a balance between privacy and information sharing among healthcare providers. Blockchain consensus mechanisms further enhance data integrity, offering a robust solution to the challenges of safeguarding sensitive health information. In the ever-evolving healthcare landscape, blockchain holds the potential to revolutionize how we manage and protect medical data.

At the edge layer, AI-based models can be crucial for applications requiring low latency or where immediate decisions are necessary. The integration of Artificial Intelligence of Things (AIoT) enhances these capabilities by combining AI decision-making with IoT connectivity and real-time data processing [15]. At the cloud layer, sophisticated AI-based models can provide in-depth data analytics, pattern recognition, and predictive modeling.

However, training robust AI-based models implies relying on medical data, which poses privacy, ownership, and regulatory challenges. Federated learning (FL) has emerged as a solution, using a centralized aggregator server and a shared global model [16].

2.2 State of the research

Thanks to technological advancements and the growing interest from healthcare organizations, several researchers have devised solutions supporting IoMT ecosystems.

Over time, researchers have focused on specific aspects, thus addressing issues related to specific layers described in Sect. 2.1 (e.g., artificial intelligence techniques, sensors integration, communication protocols, and security). While others have taken a broader perspective, concentrating on the overall system design and emphasizing architectural aspects.

Research in these areas is experiencing continuous growth. Many surveys aims outlining the state of the art in this research domain.

Dwivedi et al. [4] provide a comprehensive systematic review aimed at exploring the essential contribution of IoMT applications in improving the healthcare system. Osama et al. [5] introduce recent advances, trends, and requirements of the IoMT and Healthcare 4.0 systems. Huang et al. [17] investigate the IoMT from its concept and theory to its deployment domains, adopted technologies, and applications. Hernandez-Jaimes et al. [18] present a taxonomy of intrusion detection schemes for IoMT and discuss cybersecurity threats related to the IoMT architecture and security requirements of IoMT. Ali et al. [19] conduct a comprehensive systematic review of academic articles, delved into the multifaceted realm of artificial intelligence (AI) applications within the healthcare sector. The review encompasses an insightful analysis of the advantages, challenges, methodologies, and functionalities associated with the integration of AI in healthcare. Singh et al. [20] discuss an IoMT security architecture, including a communication protocol running on each layer.

2.3 Challenges and open issues

IoMT presents significant advantages, such as the timely detection of anomalous situations, aiding physicians in diagnostic formulation, and optimizing healthcare resources. Nevertheless, harnessing these benefits poses non-trivial challenges that must be effectively addressed.

Security and privacy. The primary concern is the security and privacy of sensitive medical data. Transmitting and storing patients' personal information through Internet-connected devices increases the risk of unauthorized access. Cybersecurity threats, such as ransomware attacks or data breaches, require a stringent implementation of advanced security protocols, robust encryption, and constant updates to protect the integrity of health data.

Interoperability. IoMT involves a wide range of devices from different manufacturers, often using different standards and protocols. Interoperability between these devices is a fundamental challenge, as the lack of standardization can hinder communication and data exchange. Solutions promoting interoperability, such as adopting open standards and common protocols, are essential to ensure seamless connectivity in the IoMT ecosystem.

Integration. To be effective, IoMT systems needs to be integrated with existing healthcare infrastructures. This integration can be complex, requiring investments in technological upgrades and staff training. Overcoming resistance to change and effectively managing the transition are critical challenges to ensure successful IoMT adoption.

Ethical issues. The use of IoMT raises significant ethical issues related to the management of patient data. It is crucial to establish ethical standards regarding the collection, use, and sharing of medical data. Transparency in data management practices, informed consent from patients, and the protection of confidentiality are fundamental aspects to consider. Balancing technological innovation with respect for patients' rights poses an ethical challenge that requires careful attention.

Accuracy and reliability. Addressing concerns about the accuracy and reliability of IoMT technologies is essential to gain the trust of healthcare professionals and patients. The quality of sensors and the methods used for signal cleaning vary widely among different wearable devices, leading to potential data inconsistency. High-quality sensors may provide precise and clean signals, while lower-quality sensors might produce noisy data that require extensive filtering and cleaning techniques. This variability necessitates robust signal processing algorithms and standardization efforts to ensure that data from various devices can be accurately integrated and utilized in medical applications. Scientific validation and continuous performance evaluation of IoMT technologies are crucial to ensure accurate and safe outcomes. Without reliable data, medical decisions could lead to misdiagnosis or inappropriate treatments. Ensuring the accuracy and reliability of IoMT technologies through ongoing assessment is paramount to maintaining the integrity of medical assessments and treatments.

Human factor. The effectiveness of IoMT solutions is heavily influenced by the users' awareness and training. Patients and healthcare providers must be adequately informed and trained to use wearable devices correctly. Without proper education, users may misuse devices, leading to inaccurate data collection and potential health risks. Additionally, a lack of awareness about the importance of consistent and correct usage can result in data gaps and reduced effectiveness of the IoMT solutions. Ensuring comprehensive training and ongoing support for users is crucial to maximize the benefits of IoMT technologies.

Finally, IoMT, as a specialized field of IoT, similarly suffers from a lack of well-defined methodologies for its standardization and implementation [21].

Tackling these challenges will require collaborative efforts from stakeholders, including healthcare professionals, researchers, regulators, and technology developers. Only through careful management of these issues can IoMT realize its full potential in the field of healthcare informatics, making a significant contribution to the improvement of medical care.

3 Animal health platforms

In recent years, there has been a huge interest in aggregating veterinary, animal health, and DNA data within diverse repositories globally. However, a substantial portion of these repositories operate in silos, prohibiting the exchange of information among different platforms. In this section, we highlight significant work and research projects in the field of animal health, emphasizing the necessity of breaking down global data silos to enhance overall health outcomes. While there exist certain technical challenges, they should do not represent an obstacle to advance in the research. Sections 3.1 and 3.2 discuss relevant research activities, while Sect. 3.3 provides the direction to future research.

3.1 Animal health European research projects

This section presents a brief summary of some relevant European research in veterinary medicine with a focus on the underlying projects of the research activities.

The project "Tracking Animal Movements and Health Records" [22] carried out by SmartAgriHubs endeavors to augment animal welfare and streamline operations within the livestock sector through the inception of a digital tool. This tool, backed by IoT and RFID technologies, facilitates real-time monitoring of animal movements within their health records. The project, initially piloted in Romania, successfully transitioned from traditional paper-based documentation to a digital system, allowing farmers to remotely scan animal transport and enhancing safety and operational efficiency. Despite facing challenges related to legal regulations on device attachments and battery longevity, the project underwent multiple design iterations. A significant insight gained was the importance of end-user feedback, which played a crucial role in shaping the system's design and adapting it to the broader needs of the animal identification industry. This feedback loop proved instrumental in refining the digital infrastructure, making it more adaptable and agile. Currently, the project aims to expand its research and development to include other species such as sheep, goats, and pigs. The ultimate goal is to further integrate this technology into the animal identification industry, with the potential to either replace or complement existing RFID technology.

The Veterinary Big Data initiative orchestrated by the European Medicines Agency (EMA) [23] and the Heads of Medicines Agencies (HMA) [24] strives to transition the European medicines regulatory network towards a more data-driven culture in the regulation of veterinary medicines within the European Union. Through digital systems, crucial data are collected and processed, serving various regulatory frameworks like the Veterinary Medicinal Products Regulation. The strategy underpins increasing system interoperability, reducing administrative burdens, and ensuring data quality and consistency across regulatory areas. As of May 2023, EMA and HMA have endorsed a workplan laying down key milestones from 2023 to 2025 for this initiative, which is set to be executed in three main phases between 2021 and 2027. The first phase emphasizes short-term data collection. The substantial data derived from digital technologies in farm management and animal healthcare is seen as a main asset that could significantly boost the regulation of veterinary medicines, thereby potentially elevating animal health standards across the EU.

The Small Animal Veterinary Surveillance Network (SAVSNET) [25] project at the University of Liverpool focuses on leveraging electronic health and environmental data for actionable research and surveillance in veterinary science. Key areas include antimicrobial use resistance, climate- and environment-related risks, and infection as well as zoonosis. With methods like real-time practice-based surveillance and scanning surveillance through diagnostic laboratories, SAVSNET aims to provide a comprehensive understanding of disease status in small animals. The data gathered are accessible to a broad audience including veterinary professionals and pet owners, and are intended to enhance awareness, preventative care, and contribute to the broader scientific understanding of animal health. One special example is the Tumor registry to analyze cancer risk of canine [26].

Finally, the latest research at the Royal Veterinary College (RVC) [27] covers a variety of topics: (1) Analyzing antibiotic resistance among Enterobacteriaceae in food-producing animals and humans in Southeast Nigeria. (2) The DAWNDINOS project which tests the locomotor superiority hypothesis for early dinosaurs. (3) The LOCATE project focused on studying the locomotion and hunting behaviors of large African carnivores. (4) The Vet Compass Project which is likely related to veterinary epidemiology, although the exact focus was not detailed on the provided page. The VetCompass eClinical Trials [28] project aims to bridge the gap in veterinary medicine where a lack of relevant published evidence hinders clinical welfare gains for dogs. The challenge lies in the fragmentation and lack of homogeneous data from varied sources. Through innovative statistical approaches applied to veterinary electronic patient records (EPRs), the project intends to evaluate the effectiveness of clinical interventions. Utilizing VetCompass' extensive data resource from about 7.5 million UK dogs, the project seeks to generate real-world evidence for key interventions, advancing the field towards evidence-based practices similar to human medicine. The HAMLET and EPIC projects [27] undertaken as well by the RVC aimed to address challenges in diagnosing and treating mitral valve disease (MVD) in dogs. A significant challenge was the accurate diagnosis in asymptomatic dogs, where a cardiac ultrasound scan by a specialist was the standard practice. The HAMLET study explored alternative diagnostic methods by evaluating serum cardiac biomarkers, while the EPIC study tested the effectiveness of Pimobendan in delaying the onset of clinical signs in dogs with preclinical MVD, demonstrating a substantial extension in the asymptomatic period by an average of 15 months. The VetCompass project [29] addresses the challenge of disparate, underutilized data in veterinary

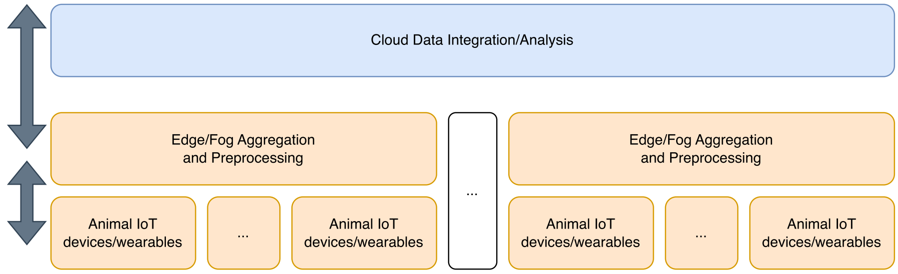


Fig. 2 Animal IoT distributed system architecture

medicine by consolidating clinical data from various veterinary practices into a singular database. This centralized data repository, comprising anonymized patient records, facilitates epidemiological research to enhance understanding, prioritize disorders based on health impact, and transition towards evidence-based veterinary medicine. By harnessing data from over 1800 practices without altering their workflow, VetCompass avoids the hurdle of data fragmentation, turning individual practice data into a valuable resource for overarching veterinary research and improved animal welfare.

3.2 Animal health IoT research projects

In this section we give a brief summary of some relevant research in veterinary medicine with a focus on the underlying projects of the research activities. The work discussed in this section partially pays into the system architecture shown in Fig. 2.

Bout et al.'s study [30] focuses on implementing a Management Information System (MIS) for a veterinary clinic to address operational inefficiencies. It utilizes predictive analysis and a segmentation algorithm to anticipate pet owners' needs based on historical medical data. The paper suggests that MIS and data analytics can be strategically used to increase revenue for business organizations, yet there is no discussion regarding standardization or compatibility with other data systems. Tamburis et al. [31] explore the use of a decision tree algorithm for automating the classification of clinical diagnoses in veterinary medicine, focusing on neoplastic diseases and zoonoses for cats and dogs. The initiative is part of a larger effort to advance Veterinary Informatics and showcases the potential of data mining techniques. However, like the previous papers, there is no emphasis on standards or compatibility issues. Wang [32] discusses a methodology to accurately and efficiently extract data from veterinary laboratory test reports using a kind of information extraction and combined with recognition algorithms. The goal is to enhance the awareness of the importance of laboratory testing and improve the quality and performance of information extraction. Despite the focus on data extraction, there is no explicit mention of adherence to standards or compatibility with other systems.

Kim et al. [33] discuss the development of a deep learning framework that performs animal sound classification to enhance animal monitoring systems. The novelty lies in the multi-task learning approach which tackles both animal species and group classification in an end-to-end learning process, showing an improvement over single-task methods in a specific dataset. However, there is no mention of adherence to any standards or compatibility with other systems. Almaza et al. [34] present a Companion Animal Health Monitoring (CAHM) system, which is an IoT-based application paired with a smart collar to improve human-pet interaction by monitoring a dog's location, heart rate, body temperature, and activity. The system was tested for functionality and usability, and it was found to satisfy the intended beneficiaries, showcasing a promising tool for both pet owners and veterinarians to monitor and manage the health of pet dogs. Kim et al. [35] discuss a livestock health monitoring system using sensors and CCTV to observe animals' health and identify specific conditions like childbearing. The proposal aims to advance livestock management by enabling early disease detection and identifying fertility in cows, which is crucial for increasing a ranch's profitability. The TerraVet project by Llaneta et al. [36] proposes a mobile and web application framework to bridge the gap between pet owners and veterinary clinics, especially during the restrictive conditions imposed by the COVID-19 pandemic. By employing GPS technology, the platform allows pet owners to locate nearby veterinarians, schedule appointments, reserve products, and consult online, while clinics can detail their services, products, and medications, enhancing the facilitation of veterinary care amidst pandemic restrictions.

Wark et al. [37] focus on the cattle breeding industry, exploring a mobile, wireless sensor/actuator network application with the aim to prevent bull fights in breeding paddocks by autonomously applying stimuli when one bull approaches another. The authors designed an animal state estimation algorithm and a wireless communication model to achieve real-time actuation and efficient mobile wireless transmissions. Both simulations and field experiments were conducted to evaluate the design's effectiveness. Along with this, Achour et al. [38] show an approach to analyze the behavior of dairy cows based on sensors and with regard to energy effiency. Carpio et al. [39] propose a novel smart farming system and application framework emphasizing animal welfare features for cows and pigs, responding to the growing public interest in farm animal welfare. Unlike existing systems that are proprietary and focused on production indicators, this framework is open, transparent, and encourages data sharing among all stakeholders. It leverages a computing and sensing framework integrating cloud and fog computing, alongside an Android-based mobile application called SmartHof. The system aims to improve human-animal interactions and enhance social interactions between animal groups on a farm, benefiting not just animal welfare but also consumers, veterinarians, and policymakers. Robinson et al. [40] discuss the ethical considerations surrounding the integration of technology with working animals in a workshop. The discussions are based on existing literature and experiences shared by the presenters and attendees, focusing on working canines. The workshop aims to collect experiences and opinions through breakout sessions, with a specific focus on understanding the opportunities for future research in this domain.

Jukan et al. [41] provide a systematic review of smart computing and sensing technologies aimed at ensuring animal welfare across various settings including domestic, farm, and wild animals. It explores the impact of these technologies on health monitoring, tracking, and communication networks to assess and improve animal welfare. The review is expected to motivate further research in this field and contribute to data, information, and communication management for animal welfare. The research of Chamberlain et al. [42] focuses on the role of trust in autonomous animal-centric robotic systems and aims to understand how to design, develop, and evaluate such systems through a Responsible Research and Innovation (RRI) approach. The paper delves into the complex nature of trust, especially in contexts where animals, humans, and intelligent systems come together in a social context. It explores the interaction and developing relationship between people and animals in the presence of autonomous systems like robotics, AI, and IoT. Karthick et al. [43] review the recent advancements in employing IoT for animal healthcare (IoTAH). It discusses how wearables and IoT devices, initially used to monitor human activities, are now being utilized to monitor animal activities. The article covers the use of biosensors and software for monitoring and maintaining animal health records, emphasizing the potential of these technologies in providing precise health status and sickness projections for animals. It explores the scope of biosensors, computing, communicating, and wearable technologies for animals, aiming to improve future research and development of animal welfare systems. Ojo et al. [44] present a review on smart farm management and monitoring systems for livestock, focusing on IoT techniques. The authors discuss various challenges faced in remote animal management due to cost and quality constraints. Through IoT and cloud services, they explore significant potential for efficient and secure farm management. The paper provides a comprehensive understanding of sensing techniques, data analysis, communication, hardware, and software used in existing smart livestock solutions. The key emphasis is on monitoring animal behavior, weather conditions, and the environment to ensure efficient livestock farming. Mancini et al. [45] advocate for the utilization of ubiquitous computing (UbiComp) technologies to improve the welfare of kenneled dogs. The authors conduct an in-depth ethnographic study at a dog rehoming center to investigate the opportunities and challenges for designing smart kennels. The proposed framework integrates monitoring, interaction, and information management to foster canine welfare in kenneled environments. Ramey et al. [46] introduce a Wearable Activity and Gait Detection (WAG’D) monitor designed to identify early signs of gait and pull force changes in sled dogs, aiming to reduce orthopedic injuries during sled races. The monitor’s feasibility was demonstrated through field studies and feedback from canine athletes involved in various sports, showing its potential application not only in sled dog racing but also in other canine athletic events and veterinary lameness detection.

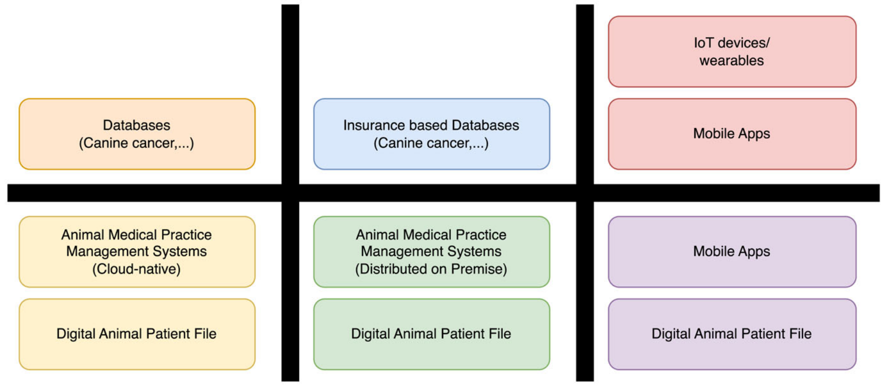
Focusing on IoT, Jukan et al. [47] show that coordinated fog computing based systems can improve the animal welfare and enhance quality of an animal’s life even if low-cost devices are used. Nevertheless, the traceability of data is not focused as down by Almeida Correia and Kleinschmidt [48]. They have shown in a proof of concept that on the one hand it is crucial to make data transactions in animal health and welfare comprehensible. On the other hand if using IoT devices like wearables which means that this distributed sensors are integrated on a two-level blockchain architecture to ensure transparency and traceability. Nevertheless, Gómez-Cárdenas et al. [49] address the important topic of identity management in fog-based networks that considers the special features of a fog-to-cloud architecture in the context of a coordinated organization of the systems. Upcoming with the fog-computing environments IoT-based systems integrated in, another challenge is arising with additional constraints to cope with focusing on the security requirements which are summarized by Yakubu et al. [50].

Further research can be found in [51], suffering from the same problems as described before in all of the current activites.

3.3 Challenges and future directions

The selected research discussed in the previos subsections highlights the field of smart technologies applied to animal welfare and healthcare. They demonstrate a strong poten-

Fig. 3 Isolation of systems and generated data



tial for data generation through various smart technology frameworks, especially leveraging IoT for monitoring and enhancing animal welfare across different settings. However, a glaring neglect towards standardization and compatibility is evident across the discussed frameworks and technologies. This includes the need to reduce the current isolation and incompatible structure of any kind of data sources compared to the current state in which mostly vendor-based isolation is performed in favor to sharing data to increase animal health (see Fig. 3):

- *Data generation.* The research collectively show a solid capacity for data generation, crucial for informed decision-making in animal healthcare. Technologies like cloud and fog computing, biosensors, and IoT devices are central to collect valuable data on animal behavior, health status, and their environment. These data can significantly contribute to improve animal welfare, assumed the data is analyzed and utilized accordingly.
- *Standard and compatibility.* Despite the promising outlook, there is a conspicuous absence of discussion around standardization and compatibility in the proposed systems and reviewed technologies. The lack of emphasis on these aspects can lead to siloed operations, where data and technologies remain limited to their individual systems without a broader, integrated application. This neglect hampers the interoperability among different systems, which is crucial for leveraging the full potential of the generated data.
- *Potential.* The lack of standardization and compatibility underscores an untapped potential in this field. By not aligning with existing standards or ensuring compatibility with other systems, the proposed frameworks risk becoming isolated solutions. This isolation hinders the broader adoption and effectiveness of these technologies, thus not fully realizing the potential of smart technologies in advancing animal welfare and healthcare.
- *Standardized approaches.* To unlock the full potential of data generated through smart technologies, there is a pressing need for standardized approaches that ensure compatibility and interoperability among different systems. This will not only foster a more collaborative environment among stakeholders but also pave the way for more comprehensive and integrated solutions that can significantly advance animal welfare and healthcare.

The trend towards storing relevant data in silos is a pervasive trend observed across many domains, particularly in veterinary and genomic research fields. These siloed data repositories, while serving as valuable resources of information, often do not focus on the broader dissemination of knowledge owing to their isolated nature. Fostering a more interconnected data ecosystem is underscored by the prospective advancements in terms of collaborative research, enhanced data analytics, and accelerated discovery in animal health and genomics.

A multitude of projects worldwide have been initiated with a focus on veterinary knowledge improvement, animal health, or DNA data. However, the practice of maintaining these data in silos poses significant potential to achieving a more holistic understanding and leveraging the collective intelligence of these distributed data sources. The current research shows several challenges associated with siloed data repositories, including but not limited to, hindered data accessibility, delayed dissemination of critical findings, and missed opportunities in performing analysis over distributed data repositories.

The discourse on the potential of interconnected data ecosystems underscores the role these ecosystems could play in fostering a more collaborative and faster research to increase animal health. By facilitating the seamless exchange of data across different repositories and stakeholders, interconnected data ecosystems will create a huge amount of benefits including enhanced data analytics, expedited discovery, and a more holistic understanding of complex veterinary and genomic processes, especially with a focus to increase the health of animals.

This means several initiatives need to be launched with the aim of bridging the data silos in veterinary research and practice, meaning a more interconnected data repository landscape. However, despite these efforts, substantial challenges remain in realizing the full potential of a collaborative data ecosystem because creating standards for data structures and APIs will take too long to take advantage. Thus, it will become necessary to create distributed and synchronized veterinary data hubs on the hand, and intermediate technologies bridging date with uncommon structures, to a flexible working standard within the data hubs.

4 Challenges in animal eHealth integration

The integration of eHealth technologies in the animal domain poses complex challenges that extend beyond technological issues and encompass a broad range of interdisciplinary considerations.

Firstly, challenges arise from the diversity of animal species, requiring flexible design approaches adaptable to various sizes, behaviors, and biological characteristics. Accurate interpretation of behavioral or physiological signals, substituting for direct communication, is crucial for effective diagnosis and monitoring. In addition, challenges related to data privacy and security are similar to those in human eHealth when a country's regulations mandate comparable protections. However, on a global scale, countries have their own specific regulations, and in some cases, there are fewer regulations governing animal data privacy and security. This discrepancy underscores the necessity for harmonized standards and protocols to ensure consistent protection of animal health data across borders. Addressing these regulatory gaps is crucial for safeguarding the integrity and confidentiality of animal health information, much like the stringent measures in place for human data.

From a technological perspective, sensors and wearable devices must be carefully designed to ensure lightness, ergonomics, and non-invasiveness, taking into account the need for long battery life, especially in rural or remote settings. Reliable connection and efficient data transmission to and from eHealth platforms can be hindered in agricultural or remote environments, requiring innovative and robust solutions. Implementing AI-based algorithms for animal data analysis requires an in-depth understanding of behavior and physiological specifics across various species, representing both a technical and scientific challenge.

Finally, platform interoperability, environmental resilience of technologies, and implementation costs pose additional issues to address. Successfully addressing these challenges necessitates interdisciplinary collaboration among technology professionals, veterinarians, farmers, and other stakeholders. Research and development of innovative technical solutions and the adoption of shared standards are essential to ensure the effectiveness and sustainable implementation of eHealth technologies in the animal domain.

5 Conclusion

This article shows the evolving trends in human and animal health platforms, emphasizing a crucial move towards a more connected, data-focused, and AI-enhanced healthcare environment. Through a detailed review of current practices and future research directions, we underline the need for setting global standards, especially regarding data format, exchange, and privacy under GDPR guidelines. Comparing human and animal health platforms reveals common challenges, mainly around data management, which are key to unlocking the benefits of AI-enabled healthcare.

The roadmap laid out in this paper outlines essential steps to build strong digital data chains, crucial for realizing a data-driven healthcare ecosystem that serves both human and animal health sectors. This analysis not only provides a clear understanding of the current scenario but also outlines a promising path forward, pinpointing crucial areas of research and development to tackle existing challenges.

The discussion highlights the core need for better compatibility between human and animal health platforms, asserting that the hurdles faced are not technical in nature but rather a matter of taking the necessary steps to ensure integration. By stressing the importance of structured data and robust analysis frameworks, our work aims to advance the discussion towards a future where human and animal health platforms are closely integrated, offering extensive benefits through a data-driven and AI-enhanced approach.

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