Integrating Hybrid Cloud Solutions in Telerehabilitation

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Abstract

The digitalization of scientific research has significantly advanced with the use of information and communication technologies, particularly in the field of physical and rehabilitation medicine and its telerehabilitation branch. A hybrid cloud platform for telerehabilitation medicine is implemented as a component-based collection of services, including a medical information system for rehabilitation, a dialog information and reference system (MedRehabBot), a predictive and analytical system for assessing rehabilitation process effectiveness, and services for optimizing rehabilitation process models. These services operate within an ontology-driven, service-oriented architecture. One of the key advantages of this type of architecture is its support for experimental design systems, where the design process of the target architecture is accompanied by scientific research. This paper examines the overall functional architecture of the platform (and its technical requirements) in the form of three interacting subsystems: medical-rehabilitation, information-analytical, and telerehabilitation. The architectural and technological organization of the platform is developed using a model that implements an advanced concept of an automated scientific research workstation. The main practical achievement is the implementation and deployment of this architectural and technological organization of the platform, which opens new opportunities for telerehabilitation in medicine.

Keywords

Hybrid cloud platform, Cloud computing, telerehabilitation, automated research workstation

1. Introduction

The advancement of modern technologies significantly impacts intellectual activities, particularly in the realm of research and development. In this context, a new class of information systems has emerged—Research and Development Workstation Environment (RDWE)—which implements an advanced concept of an automated workstation (AWS) for ongoing research and associated intelligent information technologies. These systems and concepts encompass the primary stages of the research and development lifecycle: from the semantic analysis of information materials across various subject domains to the development of innovative proposals' constructive features. A distinguishing feature of RDWE systems is their ability to adapt (problem-oriented) to different types of scientific

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activities through the integration of various functional services and the ability to add new ones within a hybrid cloud environment (platform).

A detailed analysis of the formal model, fundamental principles, and requirements for developing RDWE-class information systems is provided in [1, 2]. Among the most impressive examples of modern RDWE systems are the automated interactive system OntoChatGPT [3], developed using advanced computational linguistics technologies such as GPT-4 by OpenAI, ontology engineering support services and natural language understanding KEn [4], UkrVectōrēs [5]. The OntoChatGPT system not only expands the possibilities for intuitive human-machine interaction but also serves as a strategic tool in the RDWE context, promoting the development of innovative information systems for scientific research. A detailed overview of the OntoChatGPT RDWE system and information about its evolution can be found in [3, 6].

In early 2022, a research team from the Institute of Cybernetics (including the authors of this article) led by scientific supervisor Petro Stetsyk became one of the winners of the "Science for Security and Sustainable Development of Ukraine" competition, organized by the National Research Foundation of Ukraine (NRFU). The new project was titled "Development of the Cloud-Based Platform for Patient-Centered Telerehabilitation of Oncology Patients with Mathematical-Related Modeling" [7]. The project is dedicated to developing a hybrid cloud platform and creating on its basis an information technology for telerehabilitation of cancer patients, serving a wide range of specialists in Physical Medicine and Rehabilitation (PM&R) in the "Telerehabilitation of Cancer Patients" sector. The project's goal is to create a promising cloud platform for the telerehabilitation of cancer patients based on the application of mathematical methods of system analysis, modeling, and optimization. The choice of this direction is driven by the accelerated growth rate of cancer patients in Ukraine [8]. The main idea of the approach to creating telerehabilitation tools is the combination of artificial intelligence methods and means with mathematical methods for solving complex problems in the chosen application domain. The project's main tasks include:

- Development of a hybrid cloud platform for telerehabilitation medicine (HCP-TM) (with all its components, including services, platform, infrastructure) and its architectural and technological organization (considering all the features of the subject domain and the modern approach to digitalizing scientific research).
- Development of an information-analytical subsystem (IAS) of the HCP-TM for processing data generated in spatially distributed network sources, continuously interacting with all profile specialists, participants in the rehabilitation process, using interactive intelligent methods and tools implemented in the cloud platform. The IAS is represented, in particular, by an AWS in the field of computational linguistics with a specialized set of services and problem-oriented dataset.

This work examines the overall functional architecture of the hybrid HCP-TM (and its technical requirements) in the form of three interacting subsystems: medical-rehabilitation (MRS), information-analytical (IAS), and telerehabilitation (TRS). The architectural and technological organization of the hybrid HCP-TM is also developed using the RDWE system model.

2. Related Work

The field of telerehabilitation has experienced significant advancements through the integration of cloud computing, the Internet of Medical Things (IoMT), remote patient monitoring systems, hospital information systems, multimodal chatbots, and large language models (LLMs). Additionally, ontology-related technologies are being increasingly used to enhance these systems, providing structured and interoperable data frameworks crucial for efficient telerehabilitation.

Cloud Computing in Telerehabilitation. Cloud computing is a critical enabler for telerehabilitation, offering scalable storage and computational power necessary for handling large volumes of data. The cloud's ability to support advanced data analytics and machine learning models is crucial for personalized patient care. Studies demonstrate that cloud computing facilitates real-time updates, remote access to patient records, and seamless data integration, which are vital for efficient healthcare delivery [9, 10].

Internet of Medical Things (IoMT). IoMT integrates various wearable devices, sensors, and mobile applications to monitor patients' health metrics continuously. This ecosystem supports real-time data collection and transmission, enabling remote monitoring and timely interventions. IoMT systems are particularly effective in chronic disease management and rehabilitation, where continuous monitoring is essential for tracking patient progress and adjusting treatment plans. Research highlights that IoMT significantly improves patient outcomes by providing accurate and real-time health data [11, 12].

Remote Patient Monitoring (RPM). RPM systems leverage IoMT and cloud computing to provide comprehensive care outside traditional clinical settings. These systems collect data from various IoMT devices and use cloud-based analytics to generate actionable insights for healthcare providers. RPM enhances patient engagement and adherence to rehabilitation protocols by allowing active participation in their own care. Studies indicate that RPM reduces hospital readmissions, improves chronic disease management, and enhances patient satisfaction [13, 14].

Hospital Information Systems (HIS). Hospital Information Systems integrated with cloud and IoMT technologies create a seamless digital workstation environment for healthcare professionals. These systems streamline patient data management, clinical workflows, and administrative tasks, facilitating efficient information sharing across departments. HIS platforms typically include electronic health records (EHRs), clinical decision support systems (CDSS), and telemedicine capabilities, which are essential for effective telerehabilitation services. Implementation of HIS in telerehabilitation has been shown to improve care quality, reduce operational costs, and enhance patient safety [15].

Multimodal Chatbots and Large Language Models in Telerehabilitation. Multimodal chatbots represent the next frontier in enhancing patient interaction and care in telerehabilitation. These chatbots leverage multiple modes of input, such as text, voice, and images, to provide more interactive and intuitive patient support. Recent developments in multimodal AI have led to chatbots that can understand and respond using various data types. Advanced chatbots can process both textual and visual data to generate contextually appropriate responses, improving patient engagement and support [15, 16].

Large language models (LLMs) like GPT-4 have demonstrated significant potential in the field of telerehabilitation by providing sophisticated natural language understanding and generation capabilities. These models can facilitate various aspects of telerehabilitation, including personalized patient interactions, automated documentation, and decision support. LLMs enhance the efficiency of telehealth services by enabling more accurate and contextually relevant responses, thereby improving the quality of remote patient care [17, 18].

One key application of LLMs in telerehabilitation is their ability to assist in remote consultations. LLMs can help clinicians by transcribing and summarizing patient interactions, generating reports, and providing evidence-based recommendations. Additionally, these models can support patients directly by answering their queries, providing exercise instructions, and offering motivational support [19].

LLMs also contribute significantly to data analysis and interpretation. They can analyze patient data collected from IoMT devices to identify patterns and anomalies, enabling early detection of potential health issues and timely interventions. This capability is particularly valuable in chronic disease management and post-operative rehabilitation, where continuous monitoring and prompt response are critical [20].

Ontology-Related Technologies in Telerehabilitation. Ontology-related technologies [21, 22, 23] provide a structured framework for data management and interoperability in telerehabilitation [24, 25]. These technologies enable the integration and sharing of data across different systems and applications, enhancing the effectiveness of telerehabilitation services. Ontologies facilitate semantic data representation, allowing for better understanding and utilization of data by both machines and humans. This is particularly important in complex healthcare environments where data from various sources need to be combined and analyzed.

Ontologies in telerehabilitation are used to standardize terminologies and data models, ensuring that different systems can communicate effectively [26]. This standardization enhances data interoperability and supports advanced data analytics and decision-making processes. For example, by employing ontologies, healthcare providers can integrate patient data from electronic health records (EHRs), wearable devices, and clinical databases, leading to a more comprehensive view of the patient's health status. Research shows that the use of ontologies in healthcare can improve data quality, support personalized medicine, and facilitate the development of intelligent healthcare applications [27].

One of the significant benefits of using ontologies in telerehabilitation is the ability to create detailed and precise rehabilitation protocols that can be easily shared and understood by various stakeholders. These protocols can be tailored to individual patient needs, ensuring that each patient receives personalized care. Ontology-based systems [28] can also enhance the capabilities of decision support systems by providing a robust framework for reasoning about patient data. This can lead to more accurate diagnoses, better treatment plans, and improved patient outcomes [29].

Moreover, ontologies can support the automation of administrative and clinical workflows in telerehabilitation [30]. By using ontology-driven systems, healthcare providers can automate tasks such as appointment scheduling, resource allocation, and patient follow-ups. This not only improves efficiency but also reduces the likelihood of human errors. For instance, an ontology-based system can automatically generate reminders for patients about their rehabilitation exercises or upcoming telehealth sessions, ensuring better adherence to treatment plans. Studies have demonstrated that ontology-driven approaches can significantly streamline healthcare operations and improve the overall quality of care [30].

The integration of cloud computing, IoMT, RPM, HIS, multimodal chatbots, LLMs, and ontology-related technologies forms a comprehensive digital workstation environment that revolutionizes telerehabilitation. These technologies enhance data management, patient monitoring, and clinical decision-making, leading to improved patient outcomes and more efficient healthcare delivery. Ongoing research and development are expected to further optimize these systems, making telerehabilitation more accessible and effective.

3. Hybrid Cloud Platform for Telerehabilitation Medicine

The development of the Hybrid Cloud Platform for Telerehabilitation Medicine (HCP-TM) has been driven by the need to enhance the efficiency and effectiveness of telerehabilitation services, particularly for oncology patients. This platform integrates artificial intelligence (AI) with precise mathematical methods to optimize rehabilitation methodologies and the entire telerehabilitation process. The combination of these technologies aims to provide reliable patient assessments, effective intervention strategies, optimal rehabilitation pathways, and accurate prognostications. The primary technical requirements for creating the HCP-TM and its underlying information technology for oncology patient telerehabilitation are outlined comprehensively. These requirements ensure the system's robustness, scalability, and efficiency in managing rehabilitation processes. The detailed technical requirements can be accessed via the provided references [31].

Currently, there is a tendency to intensify scientific research both at the intersection of different subject disciplines (interdisciplinary research) and in convergence clusters (transdisciplinary research). To support these studies, important factors are the construction of knowledge-oriented information systems, improvement of research organization processes, improvement of methods and tools for ontological analysis of natural language objects using generative language models to extract knowledge from them, applied aspects of using ontologies, meta-ontologies, knowledge integration systems in transdisciplinary convergence clusters [6].

The proposed HCP-TM features a service-oriented architecture driven by ontologies [32, 33]. This architecture is implemented as a component-based collection of services, which includes two foundational subsystems: the Medical-Rehabilitation Subsystem (MRS) and the Information-Analytical Subsystem (IAS), also known as the *Cognitive Subsystem*.

The MRS includes essential functional modules such as the rehabilitation physician's workstation, patient electronic cabinet, registration modules, and other necessary components to support the rehabilitation process. A crucial part of the MRS is the telemedical support subsystem for rehabilitation activities. The main tasks of remotely controlled rehabilitation include establishing and refining optimal rehabilitation pathways, forecasting and evaluating effectiveness based on the recovery of functions, and supporting interaction among members of the interdisciplinary rehabilitation team.

The cognitive subsystem ensures the information-analytical processing of data generated from spatially distributed network sources. This is achieved through continuous interaction with all relevant specialists involved in the rehabilitation process using interactive intelligent methods and tools implemented within the hybrid HCP-TM. The IAS, a part of the patient-centric telerehabilitation cloud platform for oncology patients, is known as MedRehabBot [6, 28, 34]. It is built on a specialized set of documents related to physical and rehabilitation medicine and includes a suite of web services for context-semantic analysis of textual documents, knowledge search and classification, ontology generation in OWL, semantic trees, and graph-based knowledge bases within the domain.

MedRehabBot utilizes an information model based on a composite service represented by a three-component tuple: web services and applications, information-technology process service functions, and elements supporting the formation of an integrated knowledge environment. The IAS, with its intelligent information-analytical support functions, includes a comprehensive set of tools for evaluating the effectiveness and improving rehabilitation strategies. This allows medical professionals, researchers, and administrators to systematically enhance the telerehabilitation process, ensuring the quality-of-service delivery and the best possible outcomes for patients undergoing rehabilitation.

The information-analytical subsystem operates on the construction of a unified general model, its precise mathematical substantiation, and solving a complex set of optimization problems across the entire problem space.

From the perspective of project management, task distribution, and the functional use of the architecture, the hybrid HCP-TM can be represented by three interacting subsystems: the Medical-Rehabilitation Subsystem, the Information-Analytical Subsystem, and the Telerehabilitation Subsystem.

The general functional architecture of the HCP-TM is shown in Figure 1.

The MRS subsystem includes key functional modules such as:

- Physician’s Digital Workplace. Used by PM&R specialists, multidisciplinary rehabilitation team members, specialized healthcare physicians, and primary care physicians. This module provides a comprehensive digital interface for managing patient care and coordinating with other healthcare professionals.
- Patient’s Digital Cabinet. An online portal for patients to access their rehabilitation plans, track progress, and communicate with their healthcare providers. This module empowers patients by providing them with easy access to their rehabilitation information and resources.
- EHR Managing Module. Handles the storage, retrieval, and management of electronic health records, ensuring secure and efficient access to patient data. This module is critical for maintaining comprehensive and up-to-date medical records.

- Administration and Registry Module. Manages the administrative tasks associated with the telerehabilitation process, including scheduling, resource allocation, and documentation. Maintains a registry of patients, treatments, outcomes, and other relevant data (supports data collection and analysis, enabling the continuous improvement of rehabilitation strategies). This module ensures the smooth operation of the rehabilitation program by handling logistical and bureaucratic aspects.

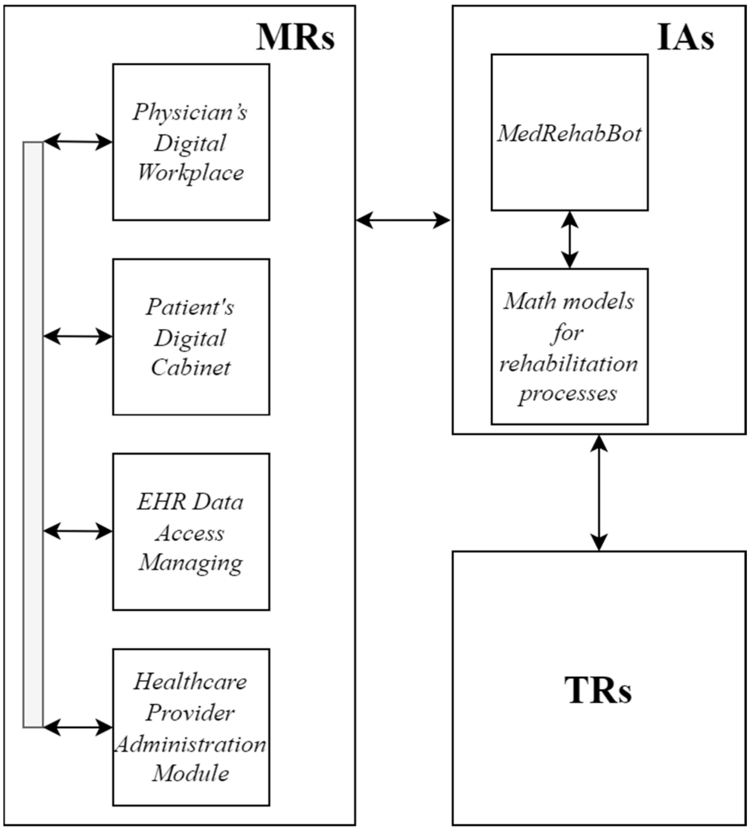

Figure 1: The General Functional Architecture of the HCP-TM.

The outlined configuration of the hybrid HCP-TM ensures the execution of several critical functions: supporting the rehabilitation process (evaluating the patient's condition and forming a rehabilitation diagnosis, predicting rehabilitation process indicators), building the optimal rehabilitation route for the patient, developing methodological foundations for supporting the rehabilitation process, and supporting interactive functions (doctor-patient-system) in dialog mode. Additionally, it accumulates and intelligently processes information from various sources, develops a set of modeling and optimization methods for the design and application of the hybrid HCP-TM, analytically processes questionnaire data, and statistically processes information.

The system also creates a "domains-scales" matrix, forms patient-centric sets of procedures and supports them in real-time, and develops diagnostic gadgets for determining the physiological and psychological state of patients. This includes video and audio sessions for telerehabilitation. The sophisticated integration of these functions within the HCP-TM framework provides a robust, patient-centered approach to telerehabilitation, enabling continuous improvement and ensuring high-quality care.

4. The Three-layer Model of the Hybrid Cloud Platform for Telerehabilitation Medicine

The Hybrid Cloud Platform for Telerehabilitation Medicine is built using an adapted three-layer model of cloud service delivery and cloud computing [35]. This model comprises the following layers.

Infrastructure Layer. Based on the Infrastructure as a Service (IaaS) model, the Infrastructure Layer provides management capabilities for processing and storage resources, communication networks, and other fundamental computing resources. This layer supports the deployment and execution of various software, including operating systems, application software, and system utilities. The infrastructure consists of three main components:

- Hardware. Includes servers, storage systems, client systems, and network equipment.
- Operating Systems and System Software. Comprises virtualization tools, automation tools, and core resource management tools.
- Middleware. Software for managing virtual operating systems.

Platform Layer. This layer, rooted in the Platform as a Service (PaaS) model, provides access to information technology platforms. These platforms include operating systems, database management systems, middleware, development, and testing tools hosted in the cloud. The entire IT infrastructure, including computing networks and storage systems, is managed by the provider. The provider determines the types of platforms available and the set of manageable parameters. Developers can use these platforms to create virtual instances, install, develop, test, and run application software while dynamically adjusting the amount of consumed computing resources.

Service Layer. The Service Layer is based on the Software as a Service (SaaS) model. At this layer, end-users (clients) access developed services and software via a thin client (through a web browser) or an application programming interface (API). This access allows users to leverage the functionalities of the platform without managing the underlying infrastructure.

The overall architectural and structural organization diagram of the hybrid HCP-TM and its components is shown in Figure 2. It includes the following components (hardware and software, external services, interface, and network components):

- HP ProLiant DL380p Gen8 Server – the high-performance server is a key component of the Infrastructure layer of the HCP-TM. Located in a specialized room at the Institute of Cybernetics, it ensures the reliability and high availability of the platform's services and resources. The server's technical specifications include: CPU

– 2x Intel® Xeon® Processor E5-2695 v2, providing high performance and multitasking capabilities; RAM – 400 GB Advanced ECC memory, enabling efficient processing of large data volumes; Storage – 2x 400 GB SSDs in RAID 1 for additional reliability, and 8x 400 GB SSDs in RAID 10 for optimized speed, and durability; Network Connection – 1 Gbps, ensuring fast access to resources and data; Power Supply – 2x 460 Watt power supplies, guaranteeing uninterrupted server operation; Uninterruptible Power Supply – Eaton 5Cs 1500VA, protecting against power outages and ensuring equipment operation during electrical failures.

- Base OS – Ubuntu 22.04.3 LTS Jammy Jellyfish serves as the base OS for the server. This version of Ubuntu is known for its stability, reliability, and wide range of supported applications for workstations and servers. It is part of the Infrastructure layer of the HCP-TM, ensuring the reliable operation and interaction of all platform components.
- Virtualization Module based on Kernel-based Virtual Machine (KVM) – KVM is a high-performance virtualization solution integrated directly into the Linux kernel. Designed specifically for the x86 architecture, KVM uses the capabilities of modern Intel and AMD processors that support hardware virtualization through Intel VT (Virtualization Technology) and AMD SVM (Secure Virtual Machine) technologies. A key feature of KVM is its ability to run multiple virtual machines with different operating systems on a single physical host, with each virtual machine using its own Linux kernel, and resources being efficiently and flexibly allocated through integration with the OS kernel. Infrastructure layer of the HCP-TM.
- Virtual Environment Management Module LibVirt – this module, along with a set of corresponding tools, provides unified management of virtual environments, regardless of their location—locally or remotely. One of the key features of LibVirt is its versatility and flexibility: it supports a wide range of virtualization systems, including Xen, QEMU, KVM, LXC, Virtuozzo, Microsoft Hyper-V, and others. This makes LibVirt an ideal choice for administrators and developers seeking a flexible and efficient solution for managing virtualization in diverse environments. Infrastructure layer of the HCP-TM.
- Virtual OSs – various specialized operating systems are used at the Platform layer of HCET. These systems play a key role in ensuring the stable and efficient operation of all platform components, including services, modules, and subsystems. The list of virtual OSs used at this level includes: Ubuntu 22.04.3 LTS Jammy Jellyfish; Alpine Linux 3.18 (a lightweight and secure operating system ideal for containers – Docker, Podman, Kubernetes); Microsoft Windows Server 2022 (a robust platform for deploying enterprise applications); Microsoft Windows 10 Pro.
- Proxy Server / VPN Server – An external virtual private server (VPS) that ensures the functioning of a virtual private network (VPN) using the modern WireGuard security protocol. WireGuard is distinguished by its high level of data protection and optimized performance. Additionally, this server operates the Nginx Proxy Manager [36] responsible for managing domains, SSL certificates, redirects, and streams. This set of tools allows for reliable, secure, and flexible access to network resources, as

well as optimizing and automating web traffic management processes. Services layer of the HCP-TM.

- Domain Name Registrar – the NIC.UA service is responsible for the registration and management of the cloud platform's domain name – https://e-rehab.pp.ua. Additionally, NIC.UA ensures the stability and security of subdomains used for various services, modules, and platform components. Choosing this registrar guarantees not only reliability but also ease of domain resource management, as well as the ability to quickly expand and adapt to new requirements and user needs. It should be noted that domain names in the pp.ua zone are provided free of charge in Ukraine. Services layer of the HCP-TM.
- Network Component of the HCP-TM – the network structure is based on the internal network of the Institute of Cybernetics, characterized by a high level of isolation. This closed network is integrated with the external Proxy Server/VPN Server through a reliable VPN tunnel based on WireGuard technology. This configuration allows for efficient and secure data exchange between the internal network of the Institute of Cybernetics and the external internet, ensuring the confidentiality, integrity, and availability of information.

The three-layer model of the HCP-TM, consisting of Infrastructure, Platform, and Service layers, provides a robust framework for delivering telerehabilitation services. This model leverages state-of-the-art technologies and methodologies to ensure scalability, reliability, and high performance. The integration of specialized hardware, advanced operating systems, virtualization technologies, and secure network configurations enables the HCP-TM to meet the demanding requirements of telerehabilitation, particularly for oncology patients. This comprehensive approach ensures that healthcare providers can deliver effective, personalized, and efficient rehabilitation services, ultimately improving patient outcomes and enhancing the quality of care.

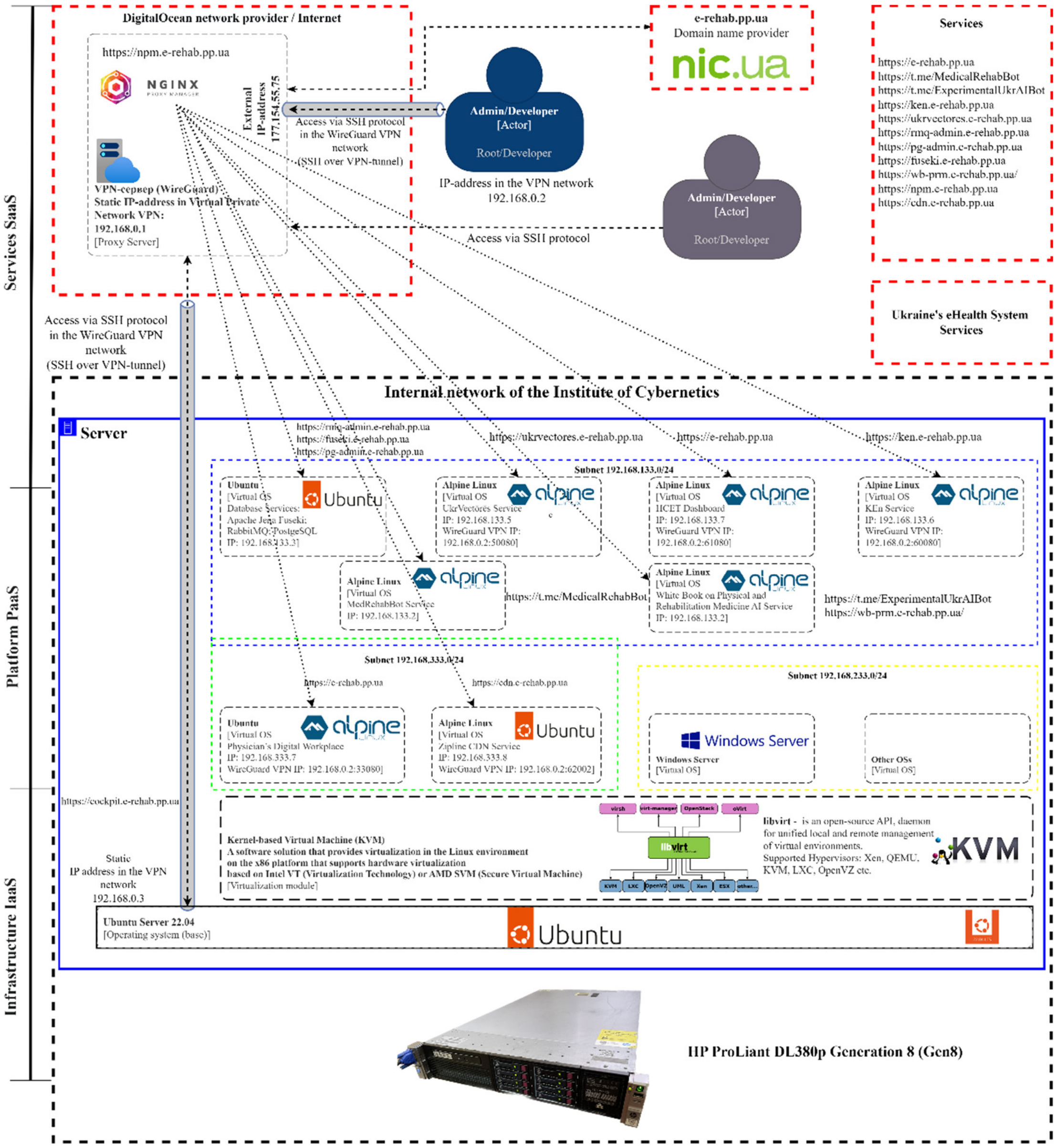

Figure 2: The Comprehensive Architectural and Structural Diagram of the HCP-TM.

5. Conclusions and Further Research

This study examined modern technological approaches to telerehabilitation medicine and its information and communication support. The application of a hybrid cloud platform with an ontology-driven service-oriented architecture enables the creation of an effective environment for remote interaction between medical personnel and patients. The architectural and technological concept of the platform is based on the principles of an advanced model of an automated research workstation. This concept has proven successful in practical implementation, demonstrating its significant potential in the field of telerehabilitation medicine.

The transition from traditional methods to the digitalization of scientific research opens new opportunities for improving the quality of medical care and ensuring access to it anytime and anywhere. The HCP-TM allows for a comprehensive integration of various advanced technologies, including AI, IoMT, and multimodal chatbots, which collectively enhance the telerehabilitation process. By facilitating seamless data management, real-time patient monitoring, and interactive functionalities, the platform ensures that healthcare providers can deliver personalized and effective care remotely.

Moreover, the use of ontology-driven frameworks within the HCP-TM enhances data interoperability and supports sophisticated data analytics and decision-making processes. This not only improves the accuracy of patient assessments and the effectiveness of treatment plans but also contributes to the overall efficiency of healthcare delivery.

Further research in this direction will promote the development of telerehabilitation and ensure its widespread application in medical practice. Continuous advancements in cloud computing, IoMT, AI, and ontology-related technologies are expected to drive innovation in telerehabilitation, making it more accessible and effective for patients globally. This ongoing evolution will ultimately lead to better health outcomes and a higher quality of life for individuals undergoing rehabilitation. Additionally, our future studies may encompass the integration of hardware support into MedRehabBot dialogue system, using state of the art circuitry type processor [38, 39]. and logical hardware technologies [40] for implementation.

The practical success of the HCP-TM in integrating these technologies underscores its potential to transform the landscape of telerehabilitation medicine. By leveraging the strengths of a hybrid cloud architecture and advanced data management techniques, the platform sets a new standard for remote healthcare services, paving the way for future innovations and improvements in this critical area of medicine.

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