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ACHIEVEMENTS AND RECENT DEVELOPMENTS

Editors:

Anatolii I. Shevchenko

Yuriy P. Kondratenko

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Artificial Intelligence: Achievements and Recent Developments

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Artificial Intelligence: Achievements and Recent Developments

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Contents

Preface

The monograph provides an overview of the main achievements and recent results in artificial intelligence (AI) technologies and systems including new theoretical findings and successful examples of AI practical implementation in different industrial and special areas (medicine, robotics, military sphere, re-building processes, etc.).

This monograph "Artificial Intelligence: Achievements and Recent Developments" consists of twelve research-oriented chapters presented by invited well-known scientists from the People's Republic of China, Ukraine, the United Kingdom, and the United States of America.

The chapter "Artificial Intelligence: Achievements and Prospects," by A. Shevchenko, M. Klymenko, and L. Baranovska, describes the current state of AI achievements and its influence on the transformation of research, social and technological processes, etc. The chapter focuses on perspectives and priority tasks of AI development and implementation. New regulatory initiatives are discussed at various levels to control AI applications and support the creation of new AI technologies, possible solutions, hardware, and algorithmic means for optimizing computations and modeling cognitive abilities.

In "Decision Support in the Field of Cyber Security Through the Use of Generative Artificial Intelligence," D. Lande, I. Svoboda, A. Feger, and L. Strashnoy present the methodology of forming causal networks through the repeated application of large language models (LLMs) with their visualization and analysis. The authors propose to create and subsequently combine two networks: first – starting from the node representing the initial state of the problem (the root cause); second – starting from the goal, working backward. The combined causal network serves as the foundation for creating desired scenarios.

V. I. Slyusar in the chapter "Applications of Large Language Models in the Military Sphere" explores the transformational impact of LLMs on modern military operations, particularly in the context of hybrid and conventional warfare. The focus is on the role of LLMs in improving decision-making, intelligence analysis, and operational efficiency. The author analyzes the future potential of LLMs for enhancing decision support systems and proposes the application of multi-agent LLMs in military technology and virtual reality (VR). The integration of LLMs into VR enables the creation of personalized, adaptive, and realistic training, significantly improving the preparation of military personnel. The chapter also examines the capabilities of multimodal LLMs for processing images, audio, and video data, as well as their use in autonomous systems and cybersecurity.

The chapter "Optimization-oriented Synthesis of Rule Bases of Intelligent Systems: Application Features for Complex Plants' Control," by Yue Zheng, Jianjun Wang, Oleksiy Kozlov, Galyna Kondratenko, and Anna Aleksieieva, addresses the optimization-oriented synthesis of rule bases (RBs) of intelligent fuzzy logic systems. The proposed approach allows the creation of fuzzy systems with an optimal set of consequents and a reduced number of rules in RBs in terms of incomplete source information due to highly efficient sequential search procedures of structural-parametric optimization. The effectiveness studies were conducted for two different intelligent control systems, particularly, for a mobile robotic platform and a floating dock.

In "The Nearest Results of Artificial Intelligence Application in Biology and Medicine: Development Trends and Implementation Risks," O. P. Mintser discusses the implementation of artificial intelligence in medicine, which is limited to a relatively small number of practical areas. The purpose of the study is to conceptualize the reasons for limitations in the use of AI, as well as the prospects and risks of AI implementation.

Ie. V. Sidenko and co-authors of the chapter "Artificial Intelligence Technologies for Efficient Solving Recognition Tasks" focus on using convolutional and recurrent neural networks for solving various recognition problems across diverse sectors. The authors analyze AI efficacy in medical diagnosis, transportation logistics, military operations, and others. By examining successful cases of AI implementations, this study highlights the role of AI in enhancing classification and recognition capabilities in real-world scenarios. Additionally, prospects for AI development, considering potential improvements and advancements to current technologies, are discovered.

The chapter "Hierarchical Decision Support System for Increasing Maritime Safety Based on Optical Color Computing Architecture," by V. Timchenko, V. Kreinovich, Y. Kondratenko, and I. Demidov, considers the basic principles of constructing logical components of the architecture of optical color computing based on estimating the dispersion of truth operands.

To implement the proposed optical architecture, a real-time changing multifactor database was generated to assess the safety of navigation in limited water areas with heavy vessel traffic. A three-level decision support system has been developed to control traffic safety and organize port ship maintenance. Possible logical operations for obtaining estimates for a specific set of input data are modeled and the effectiveness of the proposed approach due to the speed and parallelism of optical color computing is assessed.

A. V. Bukalov in the chapter "Artificial Intelligence: Effective Socionic Models of Psycho-Informational Processes and Quantum Computers" reviews theoretical and experimental studies of the quantum nature of the psyche and consciousness and discusses the author's results showing the connection between quantum and mental processes. The author introduces the concept of an elementary unit (quantum) of consciousness and proposes calculating the degree of consciousness of any living organism. Analysis of the presented data leads to the conclusion that adequate modeling and reproduction of mental processes with the manifestation of consciousness and multifunctional intelligence is possible only on quantum computers with a structure corresponding to the real structure of the psyche. It is well described by the extended information model of the psyche, proposed by the author, in socionics (or psychoinformatics) as the theory of information metabolism. The author developed the basic socionic model, introducing the coordinating function of consciousness and the description of the internal structure of mental functions, and showed that the hierarchy of these functions can be modeled as a special system from several specialized quantum processors.

Y. Zaporozhets and A. Ivanov, in "Cognitive Methodology as AI Tool for Investigation of Phenomenological Ground of Melt Electromagnetic Treatment," focus on using artificial intelligence (AI) methods to improve the efficiency of various technological and production processes in the foundry industry. Many experiments have ascertained that the melt treatment with electric current (ECT) in certain modes effectively improves structural parameters and quality of castings.

Implementation of this promising technology of melt treatment requires a deep study of the elements' interaction mechanisms of the weakly structured complex system "ECT-of-Melt" (CSEM) at all levels of its hierarchical relationships and chains of interactions. One of the most important AI approaches was used to study the phenomenological ground of the CSEM – the cognitive methodology of modeling, which is based on structuring knowledge in a specific subject domain (SD). Ontological analysis of the SD using taxonomic models ensured the creation of an ordered information platform for constructing a cognitive model (CM) of the CSEM. The CSEM CM has several essential peculiarities, particularly a multi-level hierarchical structure that covers more than a hundred concepts – vertices of the corresponding graph and about 2000 edge-connections. Such a CM cannot be used in computer models in the form of a conventional cognitive map (CMp). Therefore, the connection matrix of the primary CM was subjected to decomposition into a set of partial adjacency matrices. On their base, a hierarchical network scheme of interconnections between concepts was developed. The result of the presented development is the completion of the set of AI tools with the help of which it is possible to compile a wide range of algorithms for the cognitive study of the phenomenological basis of ECT, targeted at revealing the most effective modes of ECT of melts and obtaining high-quality castings.

The chapter "Some Aspects of the Application of Artificial Intelligence for the Recovery and Development of Ukraine," by S. Kovalevskyy, considers the AI application for the recovery and development of Ukraine, which suffered from military conflicts. The main focus is on the integration of AI into various areas of the country's life, including public administration, economy, infrastructure, health care, and education. Specific technological solutions are proposed, such as agent systems, neural networks, and decision support systems, which contribute to increasing the efficiency of recovery processes and ensuring sustainability in the conditions of post-war development. Challenges related to the implementation of AI are also discussed, including ethical, legal, and organizational aspects.

Olga Kosheleva, Vladik Kreinovich, and co-authors in the chapter "Two Is Enough, but Three (or More) Is Better: In AI and Beyond" underline that the most successful AI technique is deep learning – the use of neural networks that consist of multiple layers. It is well known that neural networks with two data processing layers are sufficient for approximating any function with a given accuracy. However, using three or more data processing layers (deep learning) makes the neural networks much more efficient. Authors show numerous examples from AI that this is a general phenomenon: two is enough but three or more is better. The authors discuss the fact that this phenomenon is universal and provide a possible explanation for such a phenomenon.

The chapter "How Free Can Artificial Intelligence Be?," by O. V. Bilokobylsky and T. V. Yeroshenko, addresses the issue of freedom in the field of AI by proposing two key perspectives: (a) whether AI can possess freedom and, if so, to what extent; (b) the conditions necessary to preserve human freedom in interactions with AI. It is argued that current AI paradigms (symbolic, perceptron, and generative), grounded in physicalist and communicative views of the mind, lack access to ontological reality, rendering them neither rational nor free. Consequently, the focus shifts to ensuring conditions for rational human social activity by mitigating AI's potential negative impacts. To achieve this, the authors propose a methodology for embedding main imperatives into AI legislation and policy.

The chapters of the monograph have been structured to provide an easy-to-follow introduction to the topics addressed, including the most relevant references, so that anyone interested in this field can get started.

This book may be useful for researchers and students who are interested in recent developments of modern control systems, robust adaptive systems, optimal control, fuzzy control, motion control, identification, modeling, differential games, evolutionary optimization, reliability control, security control, intelligent robotics, and cyber–physical systems.

We would like to express our deep appreciation to all authors for their contributions and to reviewers for their timely and interesting comments and suggestions. We certainly look forward to working with all contributors again soon.

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List of Abbreviations

ABPA	Allergic bronchopulmonary aspergillosis
AHP	Analytic hierarchy process
AI	Artificial intelligence
AIS	Abbreviated Injury Scale
ANN	Artificial neural network
ANP	Analytic network process
API	Application programming interface
ASIC	Application-specific integrated circuits
BAP	Biologically active point
BDA	Big data analysis
BDI	Belief-desire-intention
BEN	Behavior with emotions and norms
BN	Big negative
BOD	Behavior-oriented designers
BP	Big positive
CCR	Concept connections register
CGA	The Cancer Genome Atlas
CISO	Chief Information Security Officer
CM	Cognitive model
CNN	Convolutional neural network
CoT	Chain-of-thought
CPU	Central processing unit
CV	Computer vision
DARPA	Defense Advanced Research Projects Agency
DBEM	Database on Melts ECT Modes
DL	Deep learning
DM	Data mining
DMN	Default mode network
DP	Digital pathology
DSS	Decision support system
ECT	Electric current treatment

EEG	Electroencephalography
EMF	Electromotive force
FCM	Fuzzy cognitive map
FCN	Fully convolutional network
FIM	Functions of information metabolism
FL	Federated learning
FLOP	Floating point operations per second
FPGA	Field-programmable gate array
FPV	First person view
GAC	Geodesic active contours
GDPR	General Data Protection Regulation
GenAI	Generative AI
GEO	Gene Expression Omnibus
GH	Global Health
GPR	Ground-penetrating radar
GPU	Graphic processing unit
HNCut	Hierarchical normalized cuts
IAIP	Institute of Artificial Intelligence Problems
ICH	Intracerebral hemorrhage
IDS	Intrusion detection systems
IED	Improvised explosive device
IoT	Internet of Things
ISHAM	International Society for Human and Animal Mycology
IT	Information technologies
IVAS	Integrated visual augmentation system
KB	Knowledge base
KDD	Knowledge discovery in database
LAM	Large action model
LLaMA	Large Language Model Meta AI
LLM	Large language model
LRN	Local response normalization
LT	Linguistic term
MFR	Masked face recognition
ML	Machine learning
MMS	Molten metal system
MoE	Mixture of experts
MRI	Magnetic resonance imaging
NAS	Neural architecture search

NCD	Noncommunicable disease
NDVI	Normalized difference vegetation index
NEAT	Neuro-evolution of augmenting topologies
NER	Named entity recognition
NGVA	NATO Generic Vehicle Architecture
NLP	Natural language processing
NPU	Neural processing unit
OCC	Ortony, Clore, and Collins
PAM	Partial adjacency matrix
PCC	Prothrombin complex concentrate
PMEP	Phenomenological Map of Melt ECT Processes
PMS	Project management systems
PSSH	Physical symbol system hypothesis
QC	Quantum computing
RAG	Retrieval augmented generation
RB	Rule base
ReLU	Rectified linear unit
RNN	Recurrent neural network
ROI	Region of interest
S.A.R.A.H.	Smart AI Resource Assistant for Health
SaaS	Software-as-a-service
SD	Subject domain
SM	Semantic modeling
SME	Small- and medium-sized enterprise
SN	Small negative
SoC	System-on-chip
SOLO	Segmenting objects by locations
SP	Small positive
SQL	Structured query language
SVM	Support vector machine
TPN	Task-positive network
TPU	Tensor Processing Unit
TST	Ten Second Triage Tool
UAVs	Unmanned aerial vehicles
UN	United Nations
USC	University of Southern California
VGG	Visual geometry group
VoIP	Voice Over Internet Protocol
VPU	Vision processing unit

VR	Virtual reality
WME	Weapons and military equipment
WSI	Whole slide imaging
WTDS	War trauma dataset
YOLO	You only look once

1

Artificial Intelligence: Achievements and Prospects

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Abstract

This chapter is dedicated to describing the current state of artificial intelligence achievements in accordance with world trends, the extent of its influence on the transformation of social processes, the technological level of the industry, etc. Artificial intelligence is actively developing worldwide, attracting the attention of both domestic and international experts, thanks to the growing number of innovative startups, research projects, and fundamental studies. Based on an overview of the current state, the chapter focuses on consideration of the priority tasks of artificial intelligence and their possible solutions, main achievements, and perspectives of artificial intelligence implementation. New regulatory initiatives at various levels have been outlined to control the implementation and support the development of technologies, hardware, and algorithmic means for optimizing computations, as well as approaches to modeling cognitive abilities.

Keywords. Artificial intelligence, challenges, development, implementation, regulation policy, strategies.

1.1 Introduction

Over the past five years, artificial intelligence (AI) applications have become widely adopted by a broad range of users. AI is no longer seen as a technology of the near future; rather, it has a well-defined and understandable

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functionality. Nonetheless, the range of professional tasks that AI can handle continues to grow rapidly. Alongside this expansion, several questions arise concerning the development of technology, the establishment of a support ecosystem, and its management.

The authors aim to identify the applied and fundamental aspects of integrating AI into societal practice as a safe and powerful tool for the new generation, in line with ongoing scientific and technological progress. The material is presented in five sections, each of which characterizes a general area of AI-related activities. Achievements in these areas have a defining impact on the current technological state of AI.

The next section provides a brief overview of leading regulatory initiatives in the field of AI, allowing for the controlled dissemination and use of technologies in accordance with legislation or social norms. An analysis of approaches to AI development strategy is also presented, with the authors proposing their own conceptual perspective on the matter. The third section addresses the computational aspects of current artificial intelligence models, resolved through model optimization methods, improvements in hardware, and the development of new specialized computing platforms. The fourth section focuses on the analysis of current and prospective approaches to modeling intelligent activity. Proposals and specific examples of implementing individual components of a computational system that models human cognitive abilities are provided, along with identifying priority tasks in this context. The fifth section includes the general conclusions on the conducted research.

1.2 Adoption of AI Technology and Prospects for Its Development

The United Nations (UN) Advisory Body on Artificial Intelligence released its final report on September 19, 2024, offering seven recommendations to address AI-related risks and governance gaps [1].

Since the release of Microsoft-backed OpenAI's ChatGPT in 2022, the use of AI has spread rapidly, raising concerns about fueling misinformation, fake news, and infringement of copyrighted material. Only a handful of countries have created laws to govern the spread of AI tools. The European Union has been ahead of the rest by passing a comprehensive AI Act.

The AI Act is the first-ever legal framework on AI, which addresses the risks of AI and positions Europe to play a leading role globally. The AI Act provides AI developers and deployers with clear requirements and obligations regarding specific uses of AI. At the same time, the regulation seeks to reduce administrative and financial burdens for businesses and small- and medium-sized enterprises (SMEs) [2]. The AI Act is part of a wider package of policy measures to support the development of trustworthy AI, including the AI Innovation Package [3] and the Coordinated Plan on AI [4]. Together, these measures guarantee the safety and fundamental rights of people and businesses regarding AI. They also strengthen uptake, investment, and innovation in AI across the EU.

The AI Act is the first-ever comprehensive legal framework on AI worldwide. The new rules aim to foster trustworthy AI in Europe and beyond by ensuring that AI systems respect fundamental rights, safety, and ethical principles and by addressing the risks of very powerful and impactful AI models. With the development of AI in the hands of a few multinational companies, there is a danger that the technology could be imposed on people without them having a say in how it is used, the UN said in a statement. It also recommended a new policy dialogue on AI governance, creating an AI standards exchange and a global AI capacity development network to boost governance capacities. New regulatory measures should already affect almost 20% [5] of enterprises in Europe that use artificial intelligence technologies (Figure 1.1).

Among other proposals, the UN wants a global AI fund to be established, which would address gaps in capacity and collaboration. It also advocates the formation of a global AI data framework to ensure transparency and accountability. Finally, the UN report proposed setting up a small AI office to support and coordinate the implementation of these proposals [6].

The European standards for AI, as outlined in the EU AI Act, have now become a global benchmark for regulating the development and deployment of AI technologies. The alignment with EU standards is not only necessary for a country seeking full membership to harmonize its laws with the community's regulations. It is also crucial for fostering the responsibility of AI technologies at a level that directly impacts the population's well-being and economy. The AI ecosystem of Ukraine, comprising various organizations and technologies working together within the field of AI, needs to transform integration with the European Union [7]. The authorities should play a crucial role in preparing the AI industry to meet EU standards and align the ecosystem with the provisions of the EU AI Act.

This commitment is outlined in the Roadmap, which also delineates six fundamental adapting tools. Additionally, the authorities are responsible for a conducive legal environment for the advancement of AI technologies,

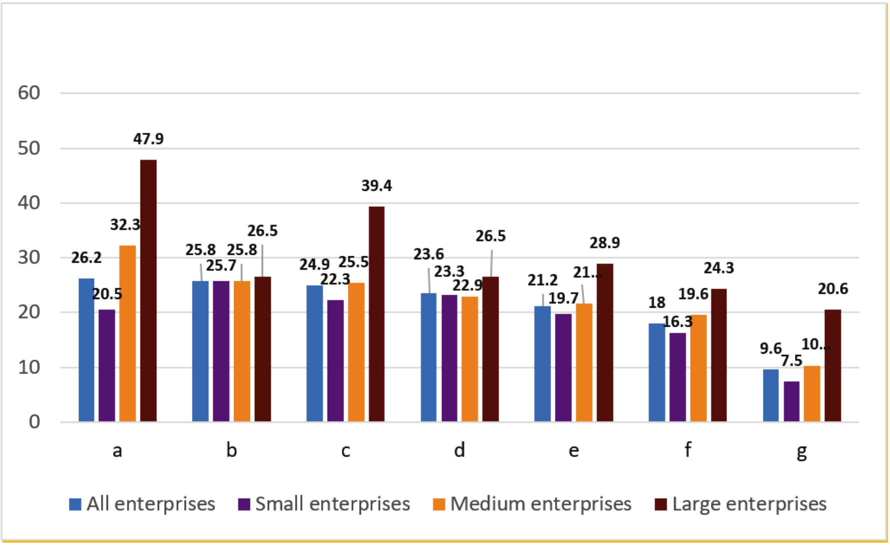

Figure 1.1 Enterprises (%) using AI technology by the type of AI technology and size class by the end of 2023: (a) automating different workflows or assisting in decision-making; (b) performing analysis of written language (text mining); (c) machine learning (e.g., deep learning) for data analysis; (d) converting spoken language into machine-readable format (speech recognition); (e) identifying objects or persons based on images (image recognition, image processing); (f) generating written or spoken language (natural language generation); (g) enabling physical movement of machines via autonomous decisions based on observation of surroundings. ⏎

ensuring that they are used within the boundaries of public safety and the protection of human rights. Ukrainian scholars have primarily focused on addressing the industry's readiness from the perspective of implementing EU law and the prospects of legal regulation [5, 8]. However, there is still limited research on the tools of adaptation outlined in the Roadmap, although some of them have been addressed in a study on harmonizing regulatory processes [9]. Note that Ukraine has the second-highest number of IT specialists (307,000) among CEE countries [10]. Also, the regulation of artificial intelligence in electoral processes is a crucial area of focus for Ukraine, especially considering its ongoing efforts to align with the European Union acquis amid a full-scale war and challenging external situation. The paper [11] explores the intersection of the EU AI Act risk-based approach and its future implementation by Ukraine, highlighting both the opportunities and risks associated with the implementation of the EU AI regulation in the context of Ukrainian electoral processes.

The strategy for AI development in Ukraine and the prospects for its implementation are outlined in the monograph [12] and in the works [13–17]. Shevchenko et al. considered implementation aspects of artificial intelligence (AI) based on the analysis of 50 national strategies for AI development in developed countries [18]. The different forms of national AI presentations and prospect domains for AI applications are discussed. Special attention is paid to NATO and Ukraine's activities in AI development and implementation at the current stage and in the future. The book chapter [19] focuses on the modern advantages in AI development and challenges in AI implementation including moral-ethical issues and dangers for human civilization. Some character examples of AI implementation in positive and negative aspects are considered as the basis for creating national and world policies in the regulation of AI development and implementation.

The article [20] provides an analysis of the specific focuses, directions, and peculiarities of the Strategy of Artificial Intelligence Development in Ukraine. The main paper's components are an analysis of the current state of the justification, development, and governmental approval of the National Strategy of AI in Ukraine; key elements and main priority areas of AI implementation according to the IAIP-project "Strategy for AI Development in Ukraine"; proposals for AI development in short- and long-term perspectives and features of the AI implementation in Ukraine during the current wartime. Special attention is paid to such focuses in AI research and development as (a) the design of AI systems based on cognitive and conscience conceptions; (b) new solutions in intelligent robotic systems for ground, underwater, and aerial applications; (c) AI perspectives in the marine industry; (d) prospective AI implementation in education; and (e) linguistic competency of AI systems. The concepts for modeling human cognitive activity proposed in the article are discussed in detail in Section 1.4 as a potential subject for further direction of research in the field of AI.

1.3 Computational Efficiency and Optimization

The diversity of transformer-based machine learning models and extensive opportunities for enhancing deep learning developments contribute to the continuous growth of new models. This is fueled by the pursuit of leading results and the increase in computational capabilities of top research centers. This trend is evident in both small models for real-time processing and large generative models. For example, the "You only look once" model (YOLO) for object recognition has grown from 50.7 million parameters in version

5 to 68.2 million in version 8, while the state-of-the-art "Real-Time Detection Transformer" model (RT-DETR-R101) reaches 76 million parameters [21, 22]. And such a trend we can see of generative models: one of the most powerful open large language models (LLMs), Llama 3.1, has 405 billion pre-trained parameters [23].

In accordance with the wide range of tasks, this demand is met by the development of specialized AI hardware accelerators, which enable significant optimization of computations within acceptable time frames. However, AI technologies are extending beyond the server and cloud infrastructure alone. Currently, there is a growing development of mobile applications operating on the Internet of Things (IoT) or edge computing principles. Such systems, in addition to hardware optimization, also require model compression techniques, enabling intelligent tasks to be performed in real time even without a broadband connection to a data processing center. Thus, these two directions of computation optimization will be discussed further.

1.3.1 Hardware AI accelerators

Hardware requirements for processing AI workloads vary depending on the use case. The challenge that system architects face is choosing the best computing cores for their AI applications. When the central processing unit (CPU) is suitable for extract, transform, and load processes and mixed data input tasks, an AI accelerator is a specialized hardware processor designed to offer greater data throughput, lower latency, and improved energy efficiency compared to conventional server processors on the market. AI accelerators include devices like graphic processing units (GPUs) and field-programmable gate arrays (FPGAs), and some types of application-specific integrated circuits (ASICs) – neural processing units (NPUs) and vision processing units (VPUs) (Figure 1.2) [24, 25].

GPUs are known for their parallel computing capabilities. The Tensor and Compute Unified Device Architecture cores (CUDA) from NVIDIA or their analogs from other manufacturers are the major computational units for machine learning algorithm accelerations. For an industry-leading inference performance or machine learning of large-scale models, GPUs based on NVIDIA Hopper architecture are widely used [26]. Among other features, H100 and H200 GPUs have a fourth-generation Tensor Core, a Tensor Memory Accelerator unit, a new CUDA cluster capability, and High Bandwidth Memory 3 (HBM3) dynamic random-access memory [27].

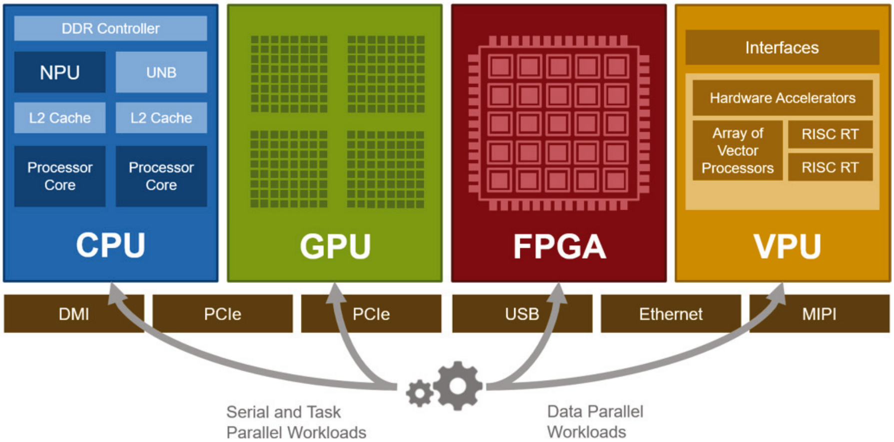

Figure 1.2 Heterogeneous platforms for advanced artificial intelligence systems. ⏎

If consumer-based GPUs require special integrated circuits to effectively process machine learning workloads, an NPU is designed to accelerate machine learning algorithms, typically by running on predictive models such as artificial neural networks or random forests. For most consumer products, the NPU will actually be integrated into the main CPU. But for more specialized industrial operations, the NPU is represented by an entirely discrete processor [28]. One of them is the Tensor Processing Unit (TPU), which has been under development by Google since 2017 and now has reached the third main version of proprietary architecture and software-as-a-service (SaaS) product of the same name: chips, systems, and software, all co-designed in-house for machine learning [29]. As alternative solutions, other leading developments are also used, such as AWS Inferentia by Amazon [30] or Ascend by Huawei [31]. A prominent class of heterogeneous system-on-chip (SoC) NPU is the VPU, which excels in embedded low-power imaging applications, covering domains such as robotics, automotive, and space. VPUs have also industrial leading developments for IoT and a wide range of tasks of video processing [32, 33]. NPUs and VPUs are types of ASICs – custom logic designed using a manufacturer's circuit libraries.

FPGAs are suitable for deep learning tasks, where we can accelerate all-reduce operations and optimize bandwidth utilization via data compression [34]. It is crucial for training performance where overhead can be a bottleneck, especially as the number of nodes increases. On this task, FPGAs can outperform GPU and NPU solutions [35]. Among these, ASICs are particularly efficient, as they consume minimal energy and can be easily tailored to specific tasks [36].

AI accelerators are applicable in both cloud servers and edge devices. Currently, the cloud serves as an ideal platform for machine learning, as it aggregates vast amounts of data from numerous sources. Meanwhile, edge computing (computing on local devices) is optimal for applications that require rapid responses. AI accelerator architecture is crucial for advanced data centers to meet the growing demands of processing and handling large datasets, such as those in machine vision, deep learning, and artificial intelligence [24]. Additionally, the power consumption of servers and data center capacity are critical considerations when designing AI accelerators [36].

The fields of artificial intelligence and quantum technology have evolved in parallel and shown great potential to enhance each other. Their integration involves using AI methods to develop algorithms for quantum computing (QC), as well as employing QC to improve AI applications. Quantum computing has the potential to revolutionize various domains as the development of user-friendly frameworks for the simulation, compilation, and execution of a quantum circuit of an artificial neural network (ANN) model on a real quantum chip [37]. However, controlling quantum systems is known to be challenging, presenting a major barrier to the widespread adoption of QC [38]. AI has opened up new opportunities for automated control of quantum systems [39, 40].

1.3.2 Model compression and edge computing

Edge computing is a networking philosophy focused on bringing computing as close to the source of data as possible in order to reduce latency and bandwidth use. Unlike the IoT devices, computing modules of this category perform tasks that are more complex but not as the generative AI (GenAI) level. The complexity of existing ANN (with convolutional, long short-term memory, transformer-based encoder−decoders, etc.) models prohibits them from being implemented in low-powered edge devices [28]. Model compression methods can reduce the high resource demands of large models, optimizing them for resource-constrained devices. Three basic methods of model compression are pruning, quantization, and knowledge distillation (Figure 1.3).

Model pruning involves removing selected network parameters to achieve a smaller model without a significant impact on performance. This technique varies from a task-specific structured approach [41] to a multi-stage pruning

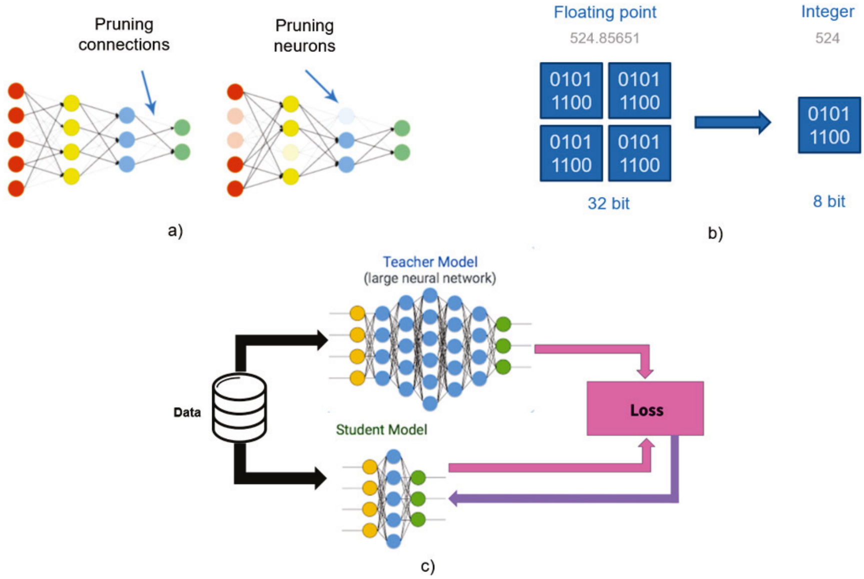

Figure 1.3 Model compression methods: (a) pruning, (b) quantization, and (c) knowledge distillation. ⏎

technique for significantly reducing model complexity while maintaining performance [42]. On the other hand, quantization provides more compact representations of neural network weights themselves. The widespread use of quantization of large language models has enabled the porting of the largest open models to mobile devices, opening up possibilities for performing generative tasks offline. Quantization usually varies compression from 16 to 1 bits and on-device fine-tuning with local data. Knowledge distillation enables the transfer of information (weights and biases) from a larger model to a smaller one, lacking the resources to learn them and allowing the smaller model to mimic the behavior of a more complex model. Tensorization is another model compression technique. It involves decomposing the weight tensors of ANN into smaller tensors with lower ranks and is used to reveal underlying patterns and structures within the data while also reducing its size. Tensorization is most useful when a model can be optimized at a mathematical level. Large-scale models are either compressed or transformed in the analyzed studies using automated frameworks like TensorFlow Lite, PyTorch Mobile, and CoreML.

A project “Development of a system for detecting explosive objects underwater” can serve as an example of a combination of AI approaches of different scales in one development. The project is carried out by the Institute of Artificial Intelligence Problems (IAIP) of the Ministry of Education and Science and the National Academy of Sciences of Ukraine. The solution aimed to help in demining of de-occupied territories of Ukraine. The development includes the creation of a new hardware and software platform for underwater unmanned vehicles, whose key features are:

- the ability to operate autonomously in case of communication loss with the operator via intermediate relay nodes;
- a significantly greater range compared to similar-class robots;
- a high degree of modularity in design;
- the use of widely available components makes it possible to assemble the robot without restricted equipment.

To meet the demands for enhanced communication reliability, a control scheme based on redundant, diverse communication channels and intermediate relay nodes has been developed. This scheme allows the operator to control both individual and multiple underwater robots simultaneously (Figure 1.4 (b)).

The prototype of the underwater unmanned vehicle is implemented based on the edge computing concept, as the robot has autonomous navigation capabilities and can detect target objects in the surrounding environment via an optical channel (Figure 1.4 (a)). A set of pre-trained machine learning models is run by the robot's onboard operating system, providing real-time data in the local environment about the robot's movement relative to surrounding objects and the classification of these objects.

The sequence of object detection and classification is stored in logs and transmitted via the available communication channel to the operator through intermediate relay nodes. This approach significantly reduces the required communication bandwidth in conditions of unstable connection and data transmission across multiple physical environments.

In addition to employing artificial intelligence methods on edge devices, this system utilizes server-side generative artificial intelligence approaches. Intelligent search task management system is hosted in the cloud and is based on a fine-tuned large language model (Figure 1.5).

The system receives natural language queries from the operator about the status of task execution by underwater robot swarm and generates a response based on the telemetry database, which is updated as data arrives from intermediate nodes. To generate a sample of relevant information, structured query language (SQL) and retrieval augmented generation (RAG) methods

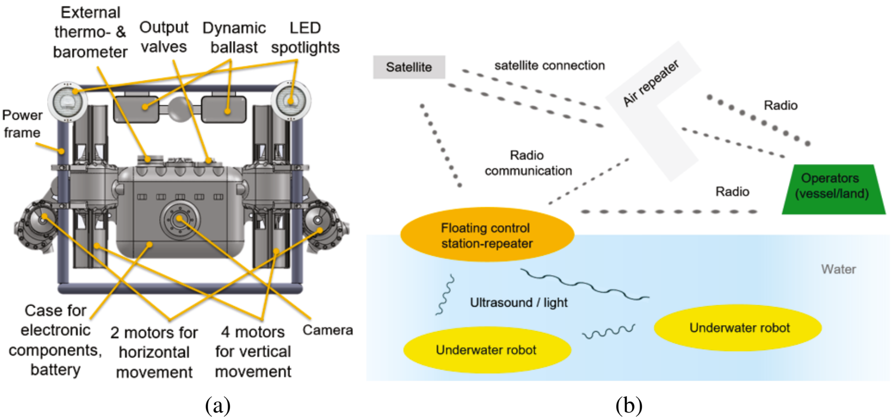

Figure 1.4 AI-powered demining system: (a) model of the underwater unit with an edge computing environment; (b) scheme of operator interaction with unmanned robotic swarm. ⏎

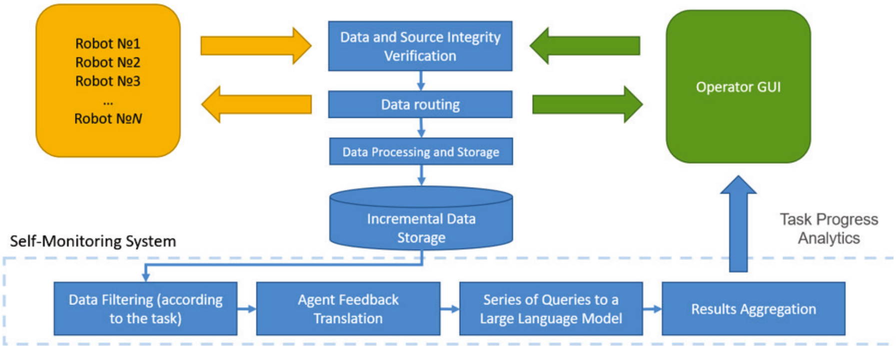

Figure 1.5 LLM usage in intelligent search task management system for operator decision-making support in the control of swarm unmanned underwater robots. ⏎

are used. The advantage of this approach is the ability to create reports on swarm operations that are not pre-defined. Among the challenges that remain is the partial low informativeness of raw telemetry data, for which a solution could be additional data filtering at remote nodes.

1.4 Modeling of Human Cognitive Abilities

The recognition of J. Hopfield and Geoffrey E. Hinton as laureates of the Nobel Prize in Physics for their discoveries in bio-inspired algorithms for artificial neural networks in 2024 highlights, firstly, the significant importance of machine learning in the contemporary scientific world and overall technological progress and, secondly, underscores the lack of new groundbreaking approaches in this field. Indeed, the results of fundamental research from more than 40 years ago are still relevant today and have continued in one form or another. Therefore, defining the object of research in the field of AI is essential for the further development of this scientific domain.

AI technologies are used in countless applications, including search engines, recommendation systems, targeted advertising, virtual assistants, autonomous vehicles, automatic language translation, facial recognition, and many more. Artificial neural networks are used for various tasks, including predictive modeling, adaptive control, and solving problems in artificial intelligence. They can learn from experience and derive conclusions from a complex and seemingly unrelated set of information. The development of artificial neural networks based on advanced technologies is one of the priority areas for developing the branches of science in all industrialized countries [43]. Ukrainian scientists such as Y. Bodyanskiy, Y. Zaychenko, and V. Sineglazov contributed significantly to the development of hybrid neural networks.

Academician Arkadii Chikrii heads the Ukrainian branch of the International Society of Dynamic Games and the Ukrainian Association of Scientists and Specialists in Automatic Control (branch of the International Federation of Automatic Control). His research team's recent developments in automated control systems, in particular, manipulation of moving objects operating in conditions of uncertainty and conflict, are relevant today [43–46]. In light of recent events, control systems of unmanned aerial/underwater vehicles have received special attention, particularly in the presence of delayed information about the state of the systems [47–57]. The problem of the approach game when the control devices fail is considered in works [53, 54], which is especially relevant in the application of unmanned aerial vehicles.

GenAI is one of the most powerful examples of machine learning. Compared to old rule-based AI applications that could only perform a single task, modern GenAI models are trained on data from many different areas, without any limitations in terms of task. Because the amount of training data is so large – OpenAI's GPT-3 was trained on more than 45 terabytes of compressed text data and the datasets for the successors are many times higher – the models appear to be creative in producing outputs [55]. For example, traditional chatbots follow scripted responses and rely on pre-defined rules to interact with users, making them suitable only for specific tasks. In contrast, modern GenAI chatbots such as ChatGPT or Google Gemini can generate human-like text, allowing for conversations that can adapt to many topics without being confined to a predetermined script. In addition, these modern chatbots can produce not only text but also images, music, and computer code based on the dataset on which they were trained [55, 56]. The hardware−software and other key aspects of AI development strategies for mobile technologies are discussed in the works [57, 58].

1.4.1 The concept of artificial consciousness as an object of scientific research

The definitions proposed in [18] reflect the provisions of the Concept for the Development of Artificial Intelligence in Ukraine [59]. At the same time, the Strategy represents the next step in implementing the tasks outlined in the Concept, necessitating a deeper understanding of the term "artificial intelligence," which is based on principles and mechanisms that mirror the functioning of the human brain, particularly its consciousness and conscience. The term "artificial consciousness" was introduced into scientific discourse as early as 1992 [60]. Subsequently, foreign experts such as John Kihlstrom, Anil Seth, Stanislas Dehaene, Michael Graziano, Taylor Webb, and others have researched the issue of artificial consciousness [61]. Ukrainian researchers began exploring these topics in 2002, when A. Shevchenko presented approaches to modeling artificial intelligence and artificial consciousness at the International Conference on "Artificial Intelligence" [62]. The ukrainian scientific school of artificial intelligence views human consciousness as a fundamental socio-cognitive system produced by brain activity, capable of perceiving and recognizing information, forming and systematizing knowledge, self-learning, and making independent motivated decisions based on tasks and circumstances while considering societal laws and rules (Figure 1.6). Consciousness shapes an individual's personality. While all these definitions compare artificial intelligence to human intelligence, they do not always accurately define the broader concept. Unfortunately, they rely solely on the functions of AI and fail to consider it as an object of research. This approach essentially reduces AI to a list of characteristics as a "black box," without clarifying what is inside. However, characteristics alone do not always allow for identifying the object of study. Therefore, artificial intelligence must be defined as an object of further scientific investigation, that is, as an element of surrounding reality.

Artificial intelligence is a function of artificial consciousness, represented by a system of algorithms that is created and controlled by it. It provides

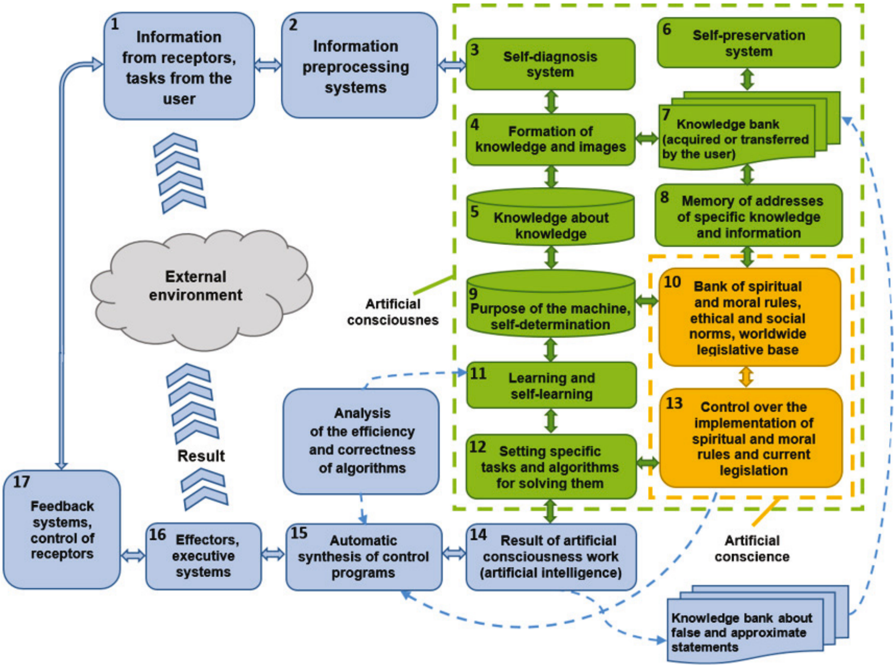

Figure 1.6 Functional model of a computer with artificial intelligence. ⏎

self-learning based on available information, acquired knowledge, societal rules and laws, and its own experiences, creating new knowledge for performing human assignments, as well as the ability to conduct self-diagnosis and justify its decisions.

Therefore, artificial intelligence is implemented as a set of functions within a weakly structured, informal system that defines its operational goals, decision-making capabilities, learning and self-learning mechanisms, knowledge acquisition, self-awareness, and more. Henceforth, we will consider that the definition of "artificial intelligence," alongside other characteristics, includes being conscious, intelligent, and making decisions in accordance with ethical, moral, and legal norms. Artificial consciousness manifests as a globally self-organizing informational creation of computational system activity, which evaluates and controls key processes occurring within it, disseminates information among various sections of the system to coordinate their operations, and ensures social and personal perception of reality.

From a technological perspective, artificial consciousness is an emergent algorithm for controlling informational processes and integrating the functions of different areas of the computational system, with the ability to override decisions made by the system. It possesses knowledge about itself and its environment, can self-learn, acquire new knowledge, and make independent decisions that align with current legislation and societal rules based on this knowledge, ensuring the internal integration and external separation of this system.

This understanding of artificial consciousness aligns with the principles of responsible AI application outlined in NATO's strategy on artificial intelligence [63], particularly with the option to deactivate the system if it begins to behave unpredictably. The concept of artificial consciousness implies the existence of artificial conscience as a mechanism to ensure the ethicality of AI decisions.

1.4.2 Approaches to modeling components of artificial consciousness

The study and modeling of consciousness (both human and artificial) leads to the problem of examining structures organized from neurons that form neural networks (biological or artificial). To work with such structures in mathematical modeling, it is convenient to transition to numerical functions. This will provide the opportunity to utilize analytical tools from mathematical analysis and graphical representations in our modeling of consciousness.

To mathematically describe this network, we solve the task of expressing and mutually uniquely recording structures through numerical functions. Such numerical representation has been proposed by Zhokhin A. S., Shevchenko A. I., and Vakulenko M. O., providing broad possibilities for analyzing and modeling neural signals [62]. Consequently, the structures of connected neurons will be expressed as numerical functions.

Let us consider the structure of the network of N interconnected neurons through synapses, which represent some form. This neural network can be depicted through a graph. Such a representation offers a convenient method for the mathematical description of real biological or technical (electronic or electrical) structures – networks in which we can identify active centers or nodes that are interconnected by links. This mathematical description abstracts the natural essence of the network, leaving only the fact of the existence of connections between the network nodes, which are the active objects of this network.

If we consider only the fact of neuron connections without the "input–output" orientation, we can represent such a network through undirected graphs, which consist of nodes connected by edges. We sequentially number all neurons with whole numbers from 1 to *N*. Let *k* and *m* be integers from 1 to *N*. We take the *k*th neuron. If it is connected to the *m*th neuron, we can introduce the indexed quantity *A*(*m*,*k*), which equals 1; if it is not connected, then *A*(*m*,*k*) = 0. Thus, for all *N* neurons, we obtain a matrix $\{A(m,k)\}$ of size $N \times N$ consisting of zeros and ones. This is the adjacency matrix, denoted as $\{A\}$.

If we consider the columns in the adjacency matrix, a rotation of $-90°$ gives us whole numbers in the binary numeral system of the type "100100…11011." For our previous compatibility matrix, the first column yields the binary number "011" (which is equal to 3 in decimal form). It is convenient for us to switch to the usual decimal representation and obtain an integer function. To construct such a numerical function related to the adjacency matrix, the following is proposed. We take the matrix $\{A(k,m)\}$ and build an integer discrete function *F*(*k*) from the discrete parameter $0 < k < (N + 1)$ in the following form:

$$F(k) = \sum_{m=1,N} 2^{m-1} A(k,m). \tag{1.1}$$

This formula provides us with the standard conversion from binary to decimal representation of an integer and is widely used in computer discrete mathematics. Essentially, it is a method for packing binary information into decimal numbers. Such a function will mutually uniquely define the neural connections in the given structure of the representation. Based on the discrete function *F*(*k*), continuous argument functions can be constructed; for example, the linear function *Lk*(*x*):

$$Lk(x) = F(k) + (F(k) - F(k-1))(x - k). \tag{1.2}$$

Here, the continuous real argument *x* lies between the integers $(k - 1)$ and *k*. If we combine all such functions for all *k* from 1 to *N*, we obtain a piecewise linear function *L*(*x*) of the continuous argument *x*, which lies in the interval of real numbers from 1 to *N*. This function can be used for graphical representation and technical applications in operations with the structures of the studied and modeled networks.

A visual representation and analysis of networks in the form of graphs will be convenient with a small number of nodes and connections. As the size of the network increases, the complexity of their analysis and description using simple graphs, without applying adjacency matrices, will grow.

Transitioning to an adjacency matrix will simplify the situation. However, an even better improvement in the situation will come from transitioning to the proposed functions $F(k)$ and $L(x)$.

These functions are single-argument functions (both integer and continuous). Therefore, for large network sizes, using such functions will have advantages over matrix and graph methods of operating and describing networks due to the information packing implemented by the construction of our functions. Moreover, we do not lose the mutual one-to-one correspondence of all these methods with the structure of our network itself.

An important argument for using such functions for network structures is that by transitioning to functions, we have the opportunity to employ mathematical methods and theories developed in mathematical analysis, as well as algorithms and their computer implementations in software packages, facilitating the creation of new programs for working with and modeling our networks and their structures.

For the case of directed networks, we take the following approach. Similarly, for directed networks with the direction of connections, we use directed graphs. We have an analogous adjacency matrix with elements $\{A(k,m)\}$, which equal 2 for an "input" connection, 1 for an "output" connection, and 0 for an isolated node. Now the columns of the compatibility matrix will yield numbers in ternary form such as "0120210...0000201." For the same three-noded graph but with directed connections, for the first node, we will have the number "012" (which is 5 in decimal). Based on these numbers, we construct a function with an integer argument. We obtain it as an integer discrete function of the form:

$$F(k) = \sum_{m=1,N} 3^{m-1} A(k,m). \tag{1.3}$$

This formula provides us with a standard transition from ternary to decimal representation of an integer, or packing information into decimal numbers. Similarly, based on the discrete function $F(k)$, we construct functions of a continuous argument x (4.1) and $L(x)$, as previously stated with analogous real arguments x.

Let us reiterate that the constructed functions will uniquely recognize structures in networks (neural) and will be convenient in mathematical operations when modeling processes related to human consciousness or the artificial consciousness of computer robots and technical systems.

Artificial consciousness is a key element of the proposed model of an intelligent computing machine. At the same time, other components have functionality that is predominantly deterministic in the algorithmic domain. An example of this is the model of artificial consciousness [14]. Artificial conscience, from a technical perspective, is a process of artificial consciousness that evaluates its own actions and intentions based on circumstances, taking into account learned rules and norms. The evaluation produces an impulsive response, the parameters of which are adjusted by subjective experience and the current activities of consciousness. The function of controlling the task setting and its execution is assigned to a system resembling human conscience – a system that monitors the establishment and achievement of goals. The component of artificial conscience for applied tasks has been implemented based on articles from the Criminal Code, which were processed into a binary tree, simplifying the identification of the most relevant action among the available rules. The result of processing a request for action is a numerical assessment ranging from neutral to negative ($-1 \ldots 0$) since there is no positive direction in the context of the rules applied. The proposed approach can be considered as an alternative to methods based on machine learning, such as the protective mechanism of LLM (for example, Llama-Guard-3–8B – a special version of the 8 billion model tuned to classify data based on content [23]) or protective subsystems of visual generative models.

AI, particularly through the advancements in machine learning and deep learning, has introduced innovative methodologies that are transforming the healthcare landscape. The ability of AI to process vast amounts of data, recognize intricate patterns, and generate predictive models has opened new avenues for research and development in medicine. Medicine, as one of the priority areas for AI implementation, is highlighted in studies [65–67]. The Institute of Artificial Intelligence Problems of the Ministry of Education and Science of Ukraine and the National Academy of Sciences of Ukraine carry out projects on the development of chatbots powered by artificial intelligence, particularly in medicine. A working group of scientists from the National Academy of Educational Sciences of Ukraine and IAIP was established to implement the project “Psychologist Chatbot” (Figure 1.7). Chatbot “Oncologist” was another one of the projects of IAIP.

A notable feature of the chatbot is its ability to conduct user screenings using methodologies that have been practically verified and approved. However, the absence of certain important human qualities essential for the profession of a psychologist, such as empathy, does not allow for a complete imitation of professional skills. Nevertheless, the implementation of the artificial consciousness model in such developments could address the remaining issues.

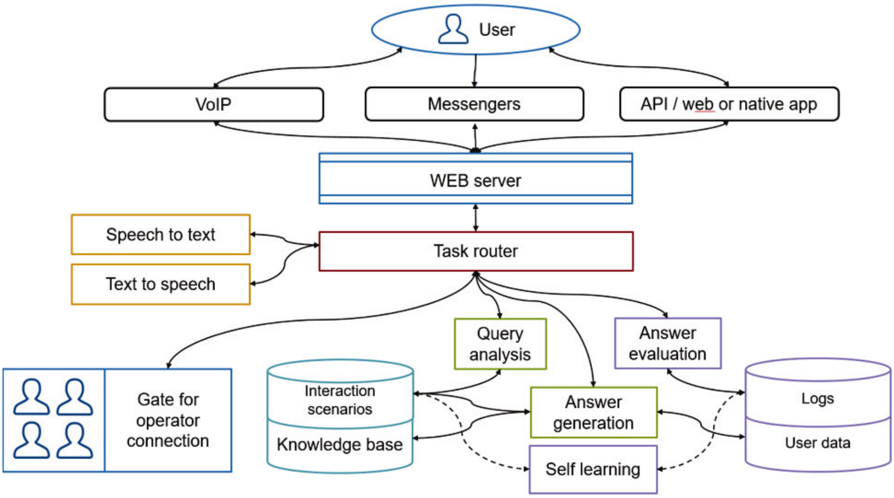

Figure 1.7 Functional diagram of main components of the AI chatbot platform. ⏎

The implemented methods include adapting the dialogue to the personal preferences and characteristics of the user and the context of the session; maintaining the anonymity of the provided information; detecting critical states and situations of the user (with notifications sent to relevant emergency assistance services); and allowing user evaluation of sessions and self-improvement based on feedback. Developed chatbots are using custom dialog platform for multichannel interaction. The main backend node is the router, which controls all the way from query input to answer delivery through active channel: voice via Voice Over Internet Protocol (VoIP) or messenger bot (Telegram, WhatsApp, Viber, etc.) or application of different platforms via single application programming interface (API). Proposals for improving chatbot response quality based on subworld embedding, as well as suggestions for the multimodality of chatbot services, are indicated in the works [66–69].

1.5 Conclusion

The current state of applied developments in artificial intelligence technologies suggests a rapid advancement and implementation of knowledge-intensive products, as evidenced by information coverage and market feedback. New regulatory initiatives at various levels have been outlined to control the implementation and support the development of technologies, hardware, and algorithmic means for optimizing computations, as well as approaches to modeling cognitive abilities.

Choosing the right hardware for AI processing depends on the specific workload with different types of AI accelerators enhancing data throughput, efficiency, and latency over standard computational units. GPUs are widely used for large-scale machine learning due to their parallel processing. NPUs excel in predictive models, FPGAs offer bandwidth efficiency for deep learning, while different ASICs provide custom, energy-efficient solutions (low-power, embedded applications, robotics, etc.). Integrating AI with quantum computing presents new possibilities but remains challenging due to the complexities of controlling quantum systems.

Examples of modern developments show the ability to adapt AI models of different modalities to tasks of server-side and distributed low-power node computation. Edge computing brings computation closer to data sources, reducing latency and bandwidth demands for complex AI tasks on low-power devices. To adapt large AI models to edge environments, compression techniques like pruning, quantization, and knowledge distillation reduce resource requirements. An example of edge AI is an underwater robot project by the Institute of Artificial Intelligence Problems in Ukraine, designed for autonomous demining tasks with enhanced communication and modularity. The system integrates edge AI for real-time object detection and cloud-based generative AI for task management, enabling efficient operator control over multiple robots even in unstable communication conditions.

The authors emphasize the importance of strategic decisions regarding the further development of artificial intelligence, one of which proposes defining the object of fundamental research, allowing for targeted scientific activities aimed at achieving breakthrough technologies. Definitions of "artificial intelligence" and "artificial consciousness" draw on the Concept for AI Development in Ukraine and emphasize mirroring human brain functions. The concept of artificial consciousness and the operational scheme of an intelligent computer based on it are proposed as the objects of research. The main components of this approach are discussed, along with examples of their practical implementation. This concept supports ethical evaluation through "artificial conscience," a function designed to assess and guide actions based on rules, with applications in various fields, such as AI-powered chatbots. Notably, AI-driven chatbots developed by Ukraine's Institute of Artificial Intelligence Problems (IAIP) aid healthcare by offering adaptive interactions, emergency response capabilities, and user feedback processing, although they lack human empathy. Future developments aim to integrate artificial consciousness for improved response quality, multimodal interactions, and ethical assessments, enhancing usability across platforms like VoIP and messaging apps.

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