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Recent Advances and Challenges in Intelligent ICT Systems: A Comprehensive Review

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ABSTRACT

Modern societies depend on Information and Communication Technology (ICT) for sustaining social, economic, and political life. Recently, integrating Artificial Intelligence (AI) and other advanced technologies into ICT systems has risen, offering smart and intelligent working capabilities to address increasing data scale, complexity, and relevance. This article surveys trends, technological advances, ethical concerns, and statistical analysis describe what constitutes an intelligent ICT system and clarifies the role of ICT technology on intelligent system. It also highlights core technologies of ICT system, the extensive integration of AI and Machine Learning, edge and cloud computing support increase, cyber-physical systems facilitating multi-dimensional data collection and interaction, proliferation of natural languages, modalities and service form growing and critical concern arises with deployment of intelligent ICT systems and framework provide support for related investigation (Rahman et al., 2024).

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1. INTRODUCTION:

Information and Communication Technology (ICT) forms the backbone of today's world enabling massive interconnectivity through voice, text, and video connectivity. Intelligence can learn from data using intelligence which characterizes today's machine learning algorithms finding great use in several verticals viz manufacturing, agriculture, supply chain management, and so on. Intelligent systems augment data by analysing it, identifying trends, and predicting future scenarios that become the base for several future forecasting and insights. Existing surveys focus on narrow aspects and form the motivation for presenting a detailed review mainly aligned with ICT and intelligence from different perspectives addressing latest developments and future direction.

This review proposes to examine advances in Intelligent ICT Systems which combines Information and Communication Technology (ICT) with Intelligent Systems (IS) by addressing advances in technology through literature and its broad applications by focusing on future directions. ICT provides the technology over which Intelligent System activities are deployed for several sectors viz Health care, Smart City, Industry 4.0 and so on. Intelligence enhances the communication over ICT by adding several data-driven activities resulting in improvements in productivity, reduction in operational time and cost reduction across many applications. (Rahman et al., 2024)

2. Theoretical Foundations of Intelligent ICT Systems:

At the core of intelligent ICT systems lie three foundational concepts: intelligence, information and communication technology (ICT), and automation. Each term possesses specific meanings and has been studied from various scientific perspectives. As of 2023, no universally accepted definition of intelligence exists, though the subject is examined in disciplines such as philosophy, logic, psychology, sociology, ethnology, anthropology, linguistics, neuroscience, artificial intelligence (AI), machine learning (ML), cybernetics, and systems theory (Santokhee et al., 2018). The term ICT denotes the hardware, software, communications, services, environments, and infrastructures used to enable, facilitate, or support the production, communication, processing, management, exchange, and storage of information. ICT supports communications between people or machines and stores or transforms information for the sake of individuals, businesses, or society. ICT may be defined broadly or narrowly depending on human intent. For instance, an intelligent computer with a monitor and communication interface may be considered an ICT system for interacting with users.

The term automation pertains to the provision of inputs and the retrieval of outputs without requiring direct human control. The scope of automation varies, which in turn affects the intelligent capabilities associated with ICT systems. The term centralised hybrid denotes the act of combining input and output materials in various stages of production, distribution, and servicing without requiring temporary storage or semi-finished goods; ATM machines act as examples of centralised hybrid systems capable of automatic banking transactions. A distributed hybrid system denotes the act of combining input and output materials across two or more locations; intelligent traffic light control or production control of vendors supplying parts to an assembly line constitute examples of distributed hybrid systems. Fully analysed models and real-time constraints are often required to support actions and build confidence during the design of these types of systems. As individuals interact with the outer world through multiple sensory channels (e.g., vision, hearing, haptics) and integrate perception across those channels for understanding and manipulation, it follows that multimodal distributed intelligent systems are a capable candidate for extending intelligence in the ICT domain. A fully analysed multimodal hybrid system integrates multiple channels of input and output across location(s) (El Kadiri et al., 2016).

3. Core Technological Advances:

Today's ICTs enable great advances in both physical and digital systems. Such systems must give special consideration to intelligence, or the capability to sense and/or react to external stimuli, through which capabilities such as supply chain forecasting, fraud detection, and vehicular traffic management are addressed. The basic premise of intelligent ICT systems is that not only can systems give direction to physical components like drones, robots, and lights, but that they can also automatically sense the need for such direction, even when no human operator is involved (Rahman et al., 2024). Normally, a person would still have to explicitly initiate and control these services, for instance by commanding that a cooling unit be turned on or off. New algorithms or methods that have emerged since early 2021 make it possible for the systems to initiate and maintain this command cycle automatically. Automated management of aerial drones in rural environments has become an active area of research.

Intelligence is one of three core descriptors of systems subject to study. Information and communications technologies (ICT) refer to composite physical and digital systems that combine electronics, computer, and communications technologies to sense and communicate information. Intelligent ICT systems are also subject to automation, whereby the system itself is capable of managing its own functioning with little or no human involvement.

3.1. Artificial Intelligence and Machine Learning in ICT:

Recent advances in Information and Communication Technologies (ICT) increasingly integrate Artificial Intelligence (AI) and Machine Learning (ML), enabling more effective and autonomous systems (Baccour et al., 2021). AI seeks to create intelligent artifacts or augment human intelligence, while ML models imitate human or animal learning in artificial settings by discovering patterns in observed data (Schmitt, 2023). Supervised, unsupervised, semi-supervised, and reinforcement paradigms exist. Systems integrate ML methods within broader ICT workflows, allowing for automation of data entry, annotation, and processing. Performance evaluation considers learning speed, data quantity, and induced knowledge quality—published datasets provide references for exhaustive evaluation, while the number of parameters and time taken to achieve a viable model reflect overall efficiency.

3.2. Human-Computer Interaction and Usability:

A usability-oriented human-computer interaction (HCI) approach concentrates on the use of systems and their design rather than their internal functioning (Issa & Isaias, 2014). HCI and usability are concerned with producing systems that interact with people in ways that are natural to the person, allowing them to express their ideas and intentions clearly. HCI uses two perspectives: objective and subjective. The objective perspective emphasizes effective human use of the system; the subjective perspective concentrates upon user perceptions. HCI is commonly used in processes that facilitate interaction between hardware/software and the users. A central focus within user-centered design is the reduction of the effort required to learn to use a system and the creation of a wide array of available interaction styles. Construction of these two goals results in the cardinal usability principles of effort, integration, and effectiveness. Systems may be characterized by the difficulty users face in learning them, how external skill in operating them contributes to use, their persistence of learned skill, and the difference between size of outcome and input (Williams et al., 2013).

3.3. Edge and Cloud Computing Architectures:

Cloud computing has emerged as an effective paradigm for meeting the rising demand for storage and computing resources in several sectors, leveraging on-demand services, self-service, and scalability (Hamdan et al., 2020). Nevertheless, cloud-based resources are inherently limited owing to latency. Consequently, a variety of edge computing paradigms have emerged, facilitating resource management between the cloud and the edge in real-time responsive applications across diverse sectors, such as smart cities, industrial systems, health systems, connected vehicles, and smart homes (Liu et al., 2019).

3.4. Cyber-Physical and Internet of Things Infrastructures:

Cyber-Physical Systems (CPS) and the Internet of Things (IoT) are expected to become integral to daily life, supporting everyday tasks and aiding in the realization of personal objectives (Esterle & Grosu, 2016). These systems originated in the 1980s with microcontrollers and embedded computing; emerging into networked, spatially-distributed, and time-sensitive components that interconnect the physical and cyber worlds via sensors and actuators. The goal of tightly coupling physical and computational elements is to increase reliability and safety, reduce resource consumption, and enhance overall efficiency (A. Yaacoub et al., 2020). Example applications include autonomous vehicles, smart cities, and energy-efficient buildings that improve safety, lessen congestion, and conserve resources (Kayan et al., 2021).

3.5. Natural Language Processing and Multimodal Interfaces:

Natural Language Processing (NLP) and multimodal interfaces are at the forefront of research and development in the field of information and communication technology. Natural language processing focuses on the understanding of human language by machines, while multimodal interfaces integrate diverse human-computer communication modalities, such as vision, dialogue, and text, and include speech, text, vision, haptics, and gestures. NLP encompasses a wide array of tasks, including the development of dialogue systems and human-machine interaction (Zhang et al., 2019).

Advancements in these areas offer transformational opportunities for human-computer interaction and automation. Nevertheless, measuring and comparing progress remains challenging. No universally accepted benchmark sets performance standards on a definite set of tasks, and evaluation metrics, while more uniformly defined than in the past, differ across objectives. Several platforms address specific dialogue system challenges, including technologies for multi-turn conversations (SAP, DSTC) and dialogue state tracking (DSTC, MultiWOZ). A multitude of large-scale multimodal datasets has been made publicly accessible, enabling federated model pre-training. Nevertheless, unified evaluation and benchmarking protocols for fusion processes, databases, and proposed architectures for performance comparison remain elusive.

3.6. Trust, Security, and Privacy Enhancements:

Uncontrolled access, malicious attacks, and untraceable activities severely undermine the security and privacy of Intelligent ICT systems. Undoubtedly, threat and attack models must first be formalized and classified before developing adequate models and techniques for a realistic and practical defense (Okporokpo et al., 2023). Intelligent ICT systems and infrastructures, which extensively utilize services from different providers in different locations, individually evolving at their own pace and exhibiting heterogeneous architectures and technologies, are susceptible to threats and security considerations tracked for all three levels of systems. Measures and techniques taken by edge and cloud computing that directly or indirectly influence services and processes at urban smart city, healthcare, and industrial manufacturing levels also affect working security and privacy postures.

Correspondingly, privacy-preserving approaches at the service level of data governance are critical for general Intelligent ICT infrastructures. Environments and phenomena of concern are sent solely within edge and cloud domains. From a governance perspective, dedicated institutions and regulations directly influencing different types of Intelligent ICT systems such as urban smart cities, healthcare, and industrial manufacturing urge policies, guidelines, and constraints to comply with norms and standards governing data handling and machine behaviour. Trust enhancement services and approaches to boost the governing institutions' and citizens' confidence in knowledge bases, approvals, data entrusted, algorithm conscience, and events dealt by different systems, thus collectively contributing to general governance throughout the Intelligent ICT life cycle (Khan Pathan, 2012).

4. Data Governance, Ethics, and Policy:

The widespread proliferation of data from multiple sources, including cameras, connected systems, and smart devices, has made data governance a pressing concern, with attention focused on six dimensions: data stewardship, provenance, quality, consent, storage, and lifecycle management (C. Aguboshim et al., 2019). Data stewardship involves policy design for data management and stewardship, taking into account the absence of a universally applicable model. Maintaining data quality, supporting effective data-driven decision-making, and ensuring compliance with legal, ethical, and organizational norms, particularly in relation to sensitive data, are vital objectives. The provenance of data and decisions constitutes an essential prerequisite for accountability, which remains a continuum of prevailing ethical considerations. Furthermore, bias, fairness, and accountability are critical subjects of discussion related to model prospecting and testing.

Governance frameworks and methodologies directed towards the establishment of ethical and trustworthy Artificial Intelligence systems should enable organizations to fulfil their obligations in relation to regulatory compliance, risk mitigation, and management of potential harm (Agbese et al., 2021). Transparency, explainability, traceability, communication, and the documentation of trade-offs are fundamental governance practices. Data governance focuses on the safeguarding of data assets during acquisition, consumption, and sharing. The aspects of data privacy, quality, access, and system reliability are further emphasized. Ethical themes encompass fairness, inclusion of diverse stakeholder views, social and environmental impacts, and the ability to prevent and remedy adverse outcomes. Additional components of oversight are the assurance of human agency as well as the security and safety of the system overall. These multiple elements jointly constitute the governance of ethical and trustworthy Artificial Intelligence systems.

5. Evaluation Methodologies and Benchmarks:

Benchmarks, datasets, evaluation protocols, reproducibility standards, and comparative scoring serve as crucial methodologies for assessing intelligent ICT systems. Recognition of their significance marks one of the first conceptual variations emerging from mainstream AI, as distinct approaches and implementations for various functions and tasks gain widespread traction (Santokhee et al., 2018). Evaluative aid sets for critically appraising algorithmic contributions to intelligent systems in urban, healthcare, and industrial domains constitute an outstanding offer within these frameworks (Kiatipis et al., 2019). Nevertheless, formal validation mechanisms specifically tailored to intelligent ICT remain singularly elusive, impeding extensive comparison among competing methodologies. Evaluation frameworks and relevant inquiries constitute prominent matters in both intelligent systems in general and intelligent ICT in particular.

6. Deployment Contexts and Applications:

Intelligent ICT systems are evaluated in actual deployment contexts; systems must adapt to physical, organizational, and societal variables. The domains of smart cities, healthcare, industry, and education serve as illustrative examples of the range of applications. Within these contexts, automated workflows can assist in decision-making, planning, control, monitoring, and other functions, thereby enhancing resilience, access, sustainability, and service quality.

Technological advances and socio-economic developments are creating new challenges for cities. Urbanization is accelerating worldwide, and cities now account for over half the global population and 70 percent of the natural resources consumed annually. Cities are the main generators of greenhouse gases because of high energy consumption (M & R, 2021). Moreover, traffic congestion is worsening, urban spaces are degraded, and the gap between the rich and poor is increasing. Smart cities represent a newly emerging paradigm to combat these challenges; cities are transforming to pursue sustainable urbanization. Sustainable urbanism encompasses smart travel, smart energy management, smart waste management, smart land-use planning, and other facets; these aspects are interrelated and dependent on robust urban governance and risk assessment (Perera et al., 2013). Smart-city architectures integrate sensing facilities, data platforms, and data analytics to gather data on urban operating conditions. Sensing facilities include fixed sensors installed on facilities such as bridges, mobile sensors deployed on vehicles and UAVs, and user-reporting applications and Internet feedback. Data platforms facilitate the collection of information from heterogeneous sources. Data analytics generates real-time insights for smart-city management.

6.1. Smart Cities and Urban Infrastructures:

The contemporary smart city is a complex framework for managing urban environments, enabling the monitoring of historical and real-time urban operations, and regulating urban equipment via integrated information systems, physical sensors, and social networks (Ismagilova et al., 2019). Information and availability are fundamental to modern urban society, and an extensive and deep information gathering and processing, enabled by social networks, open data and cases, provides basis for planning a smart city.

An urban sensing testbed for a sustainable smart city proposes a hybrid spatially-aware sensing system architecture to assist city planning smart and sustainable. A scoping review of smart city literature across domains including remote sensing, environmental tracking, information technology, utilities, big data, blockchain, and social network shows three trends: activity monitoring covers traffic flow, water flow, energy consumption, littering, and rain storm; environmental observation involves air quality, temperature, humidity, noise level, and early floods; and urban management deals with facility location, traffic planning, park selection, and urban expansion.

6.2. Healthcare and Biomedical ICT:

The healthcare system has long been one of the slowest sectors to apply modern technologies to their processes. Modern healthcare systems are still largely managed using traditional methods. Medical decision-making is based on the experience of healthcare professionals, but they can encounter difficulties such as data inaccessibility and high workloads. Detection and treatment must be temperature controlled in blood banks, but traditional systems can result in spoilage. Medical records are still maintained in paper format. Automation of routine monitoring and record-keeping tasks is expected to improve healthcare management. Healthcare data are highly sensitive and must be protected from illegal access. Security neutrality and anonymity are required. Such measures remain a challenge as healthcare systems are physically dispersed (Vyas et al., 2022).

Therefore, integrating healthcare systems and employing cutting-edge technologies to ease the burden on decision-making and routine data maintenance is a priority. Healthcare services can be categorized into four layers: prevention, monitoring, diagnosis and treatment, and hospital management. These healthcare services are divided into seven domains. Digital health involves technologies and products that either support the patient or enhance healthcare professionals' (HCPs) efficiency (Nasr et al., 2021).

6.3. Industrial and Manufacturing ICT:

Manufacturing involves managing complex processes to convert raw materials into finished products that satisfy customers' demands. Manufacturing systems are increasingly computerized and integrated; the connection of several separately automated functions leads to manufacturing systems' decentralization, flexibility, and complexity. Consequently, the automation of various manufacturing functions is receiving more attention. Some disciplines in the automation of manufacturing processes can be termed Machine Vision, Programmable Logic Controllers, CNC Systems, and Computer Aided Manufacturing. The automation of control systems using artificial intelligent methods is one of the fastest-growing disciplines, which, augmented by rapid developments in computer technology, doubles manufacturing productivity every fifteen years in developed countries (Meziane et al., 2000). In the globalized economy, there is fierce competition; therefore, manufacturing industries are depending more and more on automation to survive.

The Industry 4.0 revolution has arrived with a promise to transform manufacturing to meet the demands of such a fast-paced world. Manufacturing systems are increasingly automated, with Cyber-Physical Systems guaranteeing the physical and digital elements work together. The focus has shifted to data collection, which has led to another revolution, the Data Industry 4.0 revolution (Oliveira & Afonso, 2019).

6.4. Education and Public Services:

The direct influence of education on the development of a nation cannot be overemphasized: Education is no longer merely an acquisition of knowledge; it is more about the development of a mindset, character, and skills enabling an individual to rethink, innovate, and create new things (Fujita, 2023). The prosperity of gross domestic product (GDP) in one country is highly associated with investments in education. Governments worldwide have prioritized investing in the education system because education occupies a critical position in the strategy for building a knowledge-based economy. Massive investments in education cannot build a better education system without a proper pedagogy and the use of ICT. Knowledge stored in books is limited, cannot be updated frequently and, sometimes, is biased. ICT enables the nation to one step ahead of its neighbors through easy access to an abundance of contemporary knowledge. It is a proven fact that the Internet becomes the primary source of information for the majority of individuals and institutions worldwide. The use of a mixture of library resources and other available educational systems can raise the efficiency of using these resources significantly (Hamdan, 2018).

7. Challenges and Limitations:

Intelligent ICT systems remain a recent design trend, characteristic of other paradigms, such as cyber-physical systems and digital twins (El Kadiri et al., 2016). Consequently, while advancements in artificial intelligence, machine learning, edge computing, cloud computing, the Internet of Things, natural language processing, and several other domains confer additional capabilities, many of the challenges confronted have existed for decades. Frameworks for deploying intelligent information and communication technology adopted by broad communities can facilitate and catalyse further enhancements, provide additional open questions, and encourage exploration, widely acknowledged in other academic subfields.

This section discusses seven core outstanding challenges confronting the intelligent information and communication technology discipline: difficulties related to scalability and interoperability, transparency and accountability, robustness and safety, and sustainability. Efforts targeting substantial improvements or ultimate resolutions to these obstacles have the potential to stimulate considerable further progress within the discipline.

7.1. Scalability and Interoperability:

Intelligent Information and Communication Technology (ICT) Systems, which combine Artificial Intelligence (AI) elements with traditional ICT, offer significant benefits across sectors, but their deployment faces scalability and interoperability challenges. These systems, which may consist of heterogeneous components and multiple interacting systems, are often not considered on that scale, particularly when integrating with external systems. Moreover, rapid technological advances and an increasing number of device generations multiply these combinations, complicating large-scale deployments.

Emerging systems designed for Smart Cities and the Internet of Things (IoT) architecture have addressed scalability and interoperability concerns using a service-oriented approach and the integration of IoT solutions (Ahmed et al., 2019). Several architectural frameworks serve as generic guidelines for Intelligent ICT components and system interoperability in such contexts. These frameworks facilitate interoperability between systems within Smart Cities or IoT architectures (Hatzivasilis et al., 2018).

7.2. Transparency, Explainability, and Accountability:

Transparency is essential, along with its twin concepts of accountability and explainability. Transparency and explainability are crucial because they allow people to understand the system and the decisions made by it. These two criteria are necessary to fulfil the need for a well-structured high-level model of system responsibility (Larsson, 2019). Yet transparency alone does not provide sufficient information about responsibility. It is not enough to provide information on how the system works if the sequence of events leading up to a particular decision remains obscured. A widely recognised phenomenon, known as black-boxing, hampers the determination of what happened prior to system-initiated decisions (Tanzib Hosain et al., 2023).

7.3. Robustness, Safety, and Reliability:

In operational contexts where intelligent ICT systems interact with real-world environments, robustness, safety, and reliability assume critical importance. For systems deployed in high-stakes settings such as healthcare, finance, and security, failures can have catastrophic consequences. As intelligence, connectivity, and automation deepen, the potential for unforeseen interactions escalates, amplifying vulnerability to transient faults, design errors, cyberattacks, and adversarial manipulation (Jenihhin et al., 2019). Incomplete specifications may also result in loyalty to ambiguous objectives, enabling suboptimal or even harmful behavior.

Parallel developments in machine learning, robotics, and autonomy—that is, in areas traditionally demarcated from ICT—are influencing the evolution of the field. The pervasive adoption of ICT extends the monitoring and control of physical processes deeper into the heart of cyber-physical systems, making conventional fault-tolerance approaches unsuitable. While ICT systems were once considered for first-order properties such as algorithm correctness and computational soundness, now the focus also includes second-order properties like process safety, system security, and information privacy, with new techniques emerging to address these additional requirements.

7.4. Sustainability and Energy Efficiency:

The contemporary information and communication technology (ICT) sector exerts considerable pressure on the global environment. For example, in 2010, data centres consumed around one percent of the total electricity used globally. In 2015, this figure had risen to 1.3 percent, while projections anticipate that the demand for computing resources, which correlates closely with energy consumption, will double every five years (PROCACCIANTI, 2015). The specific energy consumption of communication networks, personal computers, and data centres is also increasing (Shuja et al., 2017). This trend is expected to accelerate with the rise of cloud computing, which intensifies the need for servers and the demand for data centre resources.

While the ICT sector is one of the largest global consumers of electrical energy, it is also considered a key enabler of techniques for improving energy efficiency in other sectors. Green computing is a holistic paradigm that promotes energy-efficient and sustainable practices, encouraging the optimal use of energy and other resources in emerging technologies such as Big Data, the Internet of Things, and cloud computing. Although energy-aware operations can decrease the sector's environmental impact, striking a balance between green policies and high-performance requirements remains a formidable challenge.

8. Emerging Trends and Future Directions:

The accelerating convergence of physical, cyber, and communication systems is giving rise to several promising and disruptive trends, and new opportunities will continue to emerge if advancements can be made in key areas. Leading contenders likely to have a substantial impact within the next five years include the further combination of cyber-physical systems with the Internet of Things (IoT), bridging the gap between autonomous systems and robotics, the addition of a digital twin layer to cyber-physical systems, and the proliferation of new natural user interface types (Amin et al., 2022). The accelerating convergence of physical, cyber, and communication systems is giving rise to several promising and disruptive trends. New opportunities will continue to emerge if advancements can be made in key areas. Leading contenders likely to have a substantial impact within the next five years include the further combination of cyber-physical systems with the Internet of Things (IoT), bridging the gap between autonomous systems and robotics, the addition of a digital twin layer to cyber-physical systems, and the proliferation of new natural user interface types (El Kadiri et al., 2016).

9. Conclusion:

Intelligent ICT System is currently undergoing significant advancement due to projects for smart cities, Industry 4.0, smart health, etc. Intelligent information and communication technologies (ICT) employ intelligence (commonly in the form of artificial intelligence [AI]) and they involve advanced information and communication technologies (ICT). They also add value by ensuring protection, communication, virtualization, and other functionalities.

The objectives of this article are to assess and summarize the advancement of intelligent ICT systems; identify associated challenges, limits, and future opportunities. Consequently, the thematic scope of the survey is wide and a diverse set of representative articles are brought to light.

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