[CP-03-018] GIS and the Internet of Intelligent Things

Abstract

The Internet of Intelligent Things (IoIT) refers to an evolution of IoT, where devices are not only connected and capable of data collection but also support advanced computing capabilities to process, filter, and analyze sensor data. These capabilities include local data processing, noise reduction, and pattern recognition to generate contextual and actionable insights in real time. The specificities of IoIT—interdependency, constrained resources, ubiquity, unattended operations, and mobility—shape how IoIT devices can be integrated with GIS systems. Interdependency allows devices to work together for real-time insights, while constrained resources demand edge computing for efficient processing. Ubiquity and mobility highlight the need for scalable GIS systems to handle widespread data streams and dynamic environments. Unattended operations thrive with intelligence embedded everywhere, enabling decentralized decision-making across devices. Federated learning enhances privacy by facilitating localized data processing while still supporting robust machine learning model development. Therefore, IoIT-enabled GIS plays a significant role in enhancing our understanding of the world as complex systems, characterised by the dynamic evolution of processes across time and space. These systems often exhibit nonlinear relationships, feedback loops, and emergent behaviours.

Author & citation

Wachowicz, M. and Cao, H. (2025). GIS and the Internet of Intelligent Things. The Geographic Information Science & Technology Body of Knowledge (Issue 1, 2025 Edition), John P. Wilson (ed.). DOI: 10.22224/gistbok/2025.1.9

Explanation

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1. Introduction

The Internet of Intelligent Things (IoIT) represents an advanced iteration of the Internet of Things (IoT), characterised by a network of interconnected devices equipped with low-cost sensors and enhanced computational capabilities. These devices perform localised data processing, enabling noise reduction, pattern recognition, and the transformation of raw sensor inputs into context-sensitive and actionable insights in real-time.

When combined with IoIT, GIS fosters a deeper understanding of our world as complex systems that often exhibit nonlinear relationships, feedback loops, and emergent behaviours, such as the interconnection between urban mobility and climate change. These

two domains are intertwined through a variety of complex systems in which factors like transportation, emissions, and environmental impacts continuously influence one another.

2. The Five Specificities of IoIT and Their GIS Applications

In the context of IoIT, the term specificity refers to the distinct characteristics that define IoIT platforms and set them apart from other types of networks and technologies. These specificities describe the unique features that shape how IoIT devices and networks perform, interact, and provide new insights. Understanding the specificities of IoIT is essential for aligning them with GIS functionalities. This alignment not only enhances data reliability and optimises interoperability but also enables more robust spatio-temporal analyses and informed decision-making processes.

2.1 Interdependency

Interdependency highlights how connected devices, actuators, sensors, and networks depend on one another to function efficiently. They often work in conjunction with one another, relying on shared data and collective functionality. The operation of one device and their sensors typically depends on the data generated by others, creating a highly interdependent system. In a smart city GIS application, various sensors (such as traffic, weather, and environmental sensors) work together to optimise urban management. A traffic sensor might detect congestion, and this data is used by nearby environmental sensors to assess air quality, triggering an alert or action if pollution levels exceed safe thresholds. The sensors' interdependence allows for dynamic decision-making based on integrated data from multiple sources.

2.2 Constrained

Constrained refers to the limitations faced by IoIT devices due to factors such as limited processing power, memory, and energy. The sensors are often small, low-cost, and designed for specific tasks, which means they must operate within certain constraints while still performing well. These limitations can impact data storage, processing capabilities, and communication bandwidth. Understanding and addressing constrained specificity is vital for maintaining reliability and energy efficiency, especially in resource-limited environments. In remote sensing applications using IoIT, devices such as drone sensors may operate with constrained power or processing capacity. A drone used for environmental monitoring might only have a limited battery life, requiring careful management of its flight path and data collection tasks to maximise its operational time. Similarly, IoIT devices in precision agriculture might need to process data from the field on-site with minimal computational power to conserve energy.

2.3 Ubiquitous

Ubiquitous refers to the concept of being present, found, or accessible everywhere at the same time. IoIT devices are designed to be everywhere, embedded in everyday objects and environments, providing continuous data streams that can be accessed anytime, anywhere. In a smart transportation system, IoIT devices, such as GPS-enabled vehicles and traffic sensors, are spread across an entire city. These devices offer ubiquitous data that can be analysed to monitor traffic flow in real-time, optimise routes, and even predict traffic

conditions. The ubiquity of these devices ensures that the data collected is constant and up-to-date, creating a comprehensive map of urban mobility.

2.4 Unattended

Unattended refers to devices that operate autonomously without the need for constant human oversight or intervention. These devices can collect, transmit, and analyse data on their own, allowing for continuous operation and monitoring. In wildlife monitoring, sensors placed in remote forests or wildlife reserves can track animal movements, temperature, and environmental conditions without requiring regular human attention. These sensors might transmit data to a cloud GIS that analyses and visualises the information for researchers or conservationists to study patterns of animal behaviour or habitat changes without needing to visit the site regularly.

2.5 Mobility

IoIT devices often support mobility, meaning they can be moved or relocated easily while still maintaining their functionality. This is especially important in GIS applications where the devices need to interact with dynamic environments. In disaster response and recovery, IoIT devices such as mobile sensors can be deployed rapidly to different locations after an earthquake, flood, or wildfire. These mobile sensors may collect data on environmental conditions, infrastructure damage, or population movements, feeding that information into a GIS system to assist with real-time mapping and decision-making for emergency responders. The mobility of these devices ensures that data is gathered in areas that are otherwise difficult to reach.

3. The Role of Standards and Interoperability

Standards and interoperability are crucial in ensuring that IoIT devices function seamlessly across different platforms, particularly in GIS applications. For interdependency, standardized communication protocols like MQTT and CoAP enable devices to share data efficiently, ensuring that environmental sensors, traffic monitors, and IoT-enabled infrastructure can interact in smart city applications. Constrained devices benefit from interoperability frameworks such as OGC SensorThings API, which allows lightweight devices with limited computational power to transmit and process geospatial data without excessive overhead. Ubiquity relies on global positioning standards like GNSS and interoperability initiatives like GeoJSON, which ensure that spatial data from diverse IoIT sources can be integrated into GIS platforms for real-time analytics.

In unattended operations, interoperability standards such as ISO 19157 (data quality) ensure that remote sensors maintain consistent data accuracy without human oversight. Mobility is supported by edge computing frameworks like EdgeX Foundry, which standardize how IoIT devices process geospatial data locally before transmitting relevant insights to GIS platforms. Intelligence Everywhere frameworks leverage interoperability through federated learning techniques, such as Google’s TensorFlow Federated, which enables multiple IoIT devices to train AI models collaboratively while preserving data privacy. These examples highlight how robust standards and interoperability mechanisms are essential in overcoming IoIT-specific challenges, enhancing data integration, security, and efficiency in GIS applications.

4. The Role of OTA (Re)Programming Across IoIT Specificities

Over-the-Air (OTA) (re)programming is essential for managing the interdependency of IoIT devices, ensuring seamless coordination between sensors, actuators, and networks. When multiple devices rely on shared data for real-time decision-making, OTA updates can synchronize their operations by refining data processing algorithms or adjusting communication protocols. In a smart city GIS application, for example, traffic and environmental sensors must adapt to changing conditions—OTA updates can optimize traffic signal timing based on congestion patterns or recalibrate air quality sensors in response to seasonal variations. Similarly, for constrained IoIT devices, OTA updates help overcome hardware limitations by optimizing software efficiency, compressing data for transmission, or deploying lightweight AI models that enhance device functionality without increasing computational burden. In precision agriculture, for instance, OTA updates can adjust irrigation sensor algorithms to improve water conservation strategies based on updated climate models.

For ubiquitous IoIT systems, OTA ensures that continuously operating devices remain up to date without disrupting data collection. GPS-enabled IoIT sensors in transportation networks, for example, can receive OTA firmware updates to improve route optimization algorithms or integrate new traffic datasets. In the case of unattended devices, OTA is critical for maintaining autonomous operation, allowing sensors in remote or hazardous locations—such as deep-sea monitoring buoys or wildfire detection networks—to receive software patches without human intervention. Lastly, OTA supports mobility by enabling real-time adaptability in moving IoIT devices, such as drones or autonomous vehicles, ensuring they stay synchronized with GIS platforms while operating in dynamic environments. A fleet of emergency response drones, for example, can receive OTA updates to refine their navigation algorithms or prioritize data collection in high-risk areas, enhancing their effectiveness in crisis situations.

5. Key Functionalities for GIS to Integrate with IoIT

5.1 Edge Computing

To handle massive real-time data from IoIT devices, GIS platforms must adopt edge computing, enabling localized processing for faster decision-making (Franchi et al., 2024). In wildfire monitoring, IoIT drones with thermal sensors and AI-powered edge processors can autonomously map fire perimeters and predict spread, reducing response time. Smart cities benefit from autonomous vehicles using edge-enabled GIS to process road conditions and traffic in real time, optimizing routes without cloud delays.

Beyond efficiency, edge computing expands GIS into extreme environments. Lunar rovers analyze terrain and adjust navigation without Earth-based processing, while underwater drones map coral reef changes and detect methane leaks autonomously. By embedding intelligence at the edge, IoIT-GIS systems become faster, more adaptive, and capable of real-time, autonomous decision-making.

3.2 Scalability

Scalability is a critical factor for the successful integration of GIS and IoIT systems, as it enables these systems to handle increasing amounts of data and devices over time. As IoIT networks expand, the volume of data generated by connected devices grows exponentially, requiring GIS platforms to scale efficiently without compromising performance. Scalable GIS can manage large datasets from diverse IoIT sources, such as sensors, cameras, and environmental monitors, and can process and analyse this data in real-time. Scalability also ensures that GIS can accommodate new devices or data streams without needing complete overhauls, making it adaptable to changing technological landscapes. This ability to grow seamlessly is essential for applications in smart cities, industrial automation, and environmental monitoring, where data sources continuously increase and evolve.

3.3 Intelligence Everywhere

Intelligence Everywhere is predicated on the seamless integration of IoIT networks transporting a vast amount of data streams through many computing resources across an edge-to-cloud continuum, relying on the orchestration of distributed machine learning models (Cao et al. 2019). The result is an interconnected and collective intelligent ecosystem where devices, systems, services, and users work together to support informed decision-making, adaptive responses to dynamic environments, and optimisation of resources across various GIS platforms. Figure 1 illustrates the vision of an ecosystem where the global Intelligence Everywhere learning paradigm encompasses many IoIT-based GIS platforms that are co-existing and sharing resource, analytical, learning, and data life-cycle capabilities towards an overarching goal of enabling data diversity, enhancing contextual understanding, and supporting distributed decision-making.

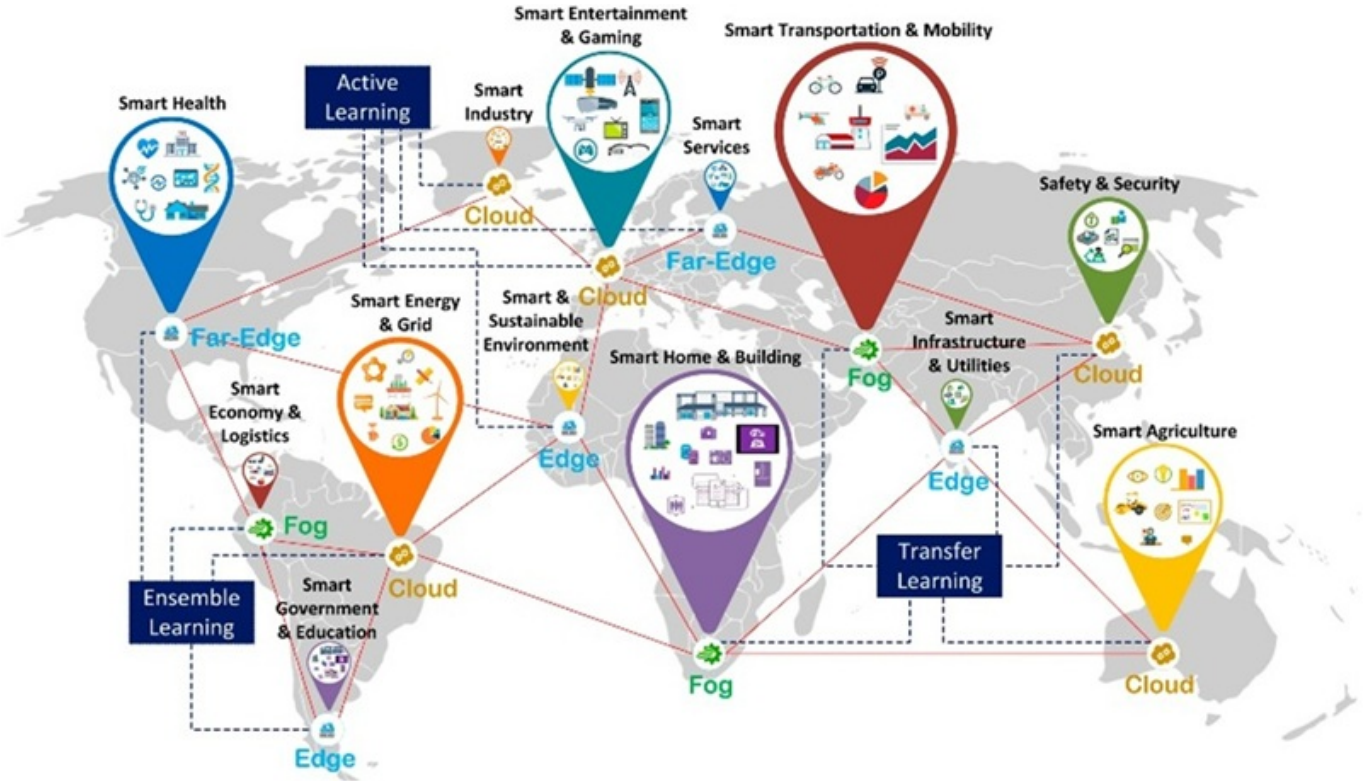


Figure 1. Intelligence Everywhere Ecosystem. Source: authors.

Intelligence Everywhere refers to the seamless integration of AI-driven decision-making across distributed IoIT networks, enabling real-time, context-aware responses without relying solely on centralized cloud computing. It leverages a combination of edge AI, TinyML (Tiny Machine Learning), and federated learning to ensure that data is processed close to its source, reducing latency and enhancing adaptability in dynamic environments (Zhang et al. 2021).

An Intelligence Everywhere ecosystem can also combine multiple machine learning models to enhance accuracy and robustness, addressing the complexities of noisy and heterogeneous data sources (ensemble learning). By aggregating outputs from various machine learning models, this approach enhances prediction reliability, especially in dynamic environments such as smart cities. For instance, a combination of decision trees, support vector machines (SVM), and neural networks can be employed to predict traffic congestion, leveraging historical data, weather conditions, and real-time sensor inputs. Aggregating the predictions from these diverse models results in more robust and accurate traffic forecasts, improving decision-making for traffic management and urban planning.

In scenarios with limited resources or large volumes of incoming data, an IoIT-enabled GIS platform helps mitigate information overload and optimise model training by prioritising which data should be labelled or analysed, particularly in real-time applications. (Li et al. 2019). For example, in monitoring environmental conditions or traffic flow, active learning enables the system to focus on the most relevant or uncertain data points. This targeted approach improves prediction accuracy and accelerates decision-making processes.

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