

CYBERSECURITY IN ERA OF INDUSTRIAL TACTILE INTERNET (TI)

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Abstract :

*This article highlights the **transformative role of the Internet of Things (IoT) in industry**. It emphasises the capacity of IoT to deliver **control information, tactile feedback, and real-time actions**, which are essential elements for the digitalisation of modern industrial processes. The paper analyses the technological changes from traditional systems to advanced wireless solutions, focusing on the integration of **5G platforms and the implementation of ultra-reliable tactile communications**. Furthermore, it details how the **iNGENIOUS project** utilises these technologies to optimise industrial operations, safety, and efficiency through tactile IoT solutions and flexible automation.*

Keywords: Cybersecurity, Internet of Things (IoT), Tactile Internet, Industry 4.0, 5

1. INTRODUCTION

In the initial phases of mobile wireless communications—beginning with 2G networks and early Wi-Fi—these technologies were primarily utilized for data collection and message exchange. Over time, they evolved into central components of the current industrial environment, connecting both the wide-scale population and intelligent machines and devices, thereby establishing the fundamental concept of the Internet of Things (IoT). Today, IoT is present across multiple sectors, including health, entertainment, and the industrial sector, where it facilitates the critical transition toward Industry 4.0. Within the industrial sector, IoT is specifically defined as an interconnected network of sensors, monitoring devices, and systems. These systems are capable of continuously acquiring, analysing, and reacting to field data, ensuring that productive processes remain stable and efficient. Should deviations occur, the IoT system possesses the capability to issue automated alerts, allowing for swift correction of the workflow. The advancement of wireless communications and 5G technology has been pivotal, enabling the emergence of the Tactile Internet. This adds an essential supplementary dimension to communication: the real-time transmission of haptic information, such as touch, movement, and vibration, alongside conventional audio-visual data and control commands. This type of communication, which is ultra-reliable and features extremely low latency, has unlocked new possibilities for remote, interactive systems involving humans and machines, thereby revolutionizing transportation, healthcare, and industry. 5G networks introduce enhanced flexibility for industrial applications. They eliminate the constraints typically imposed by wired networks, making it possible to integrate advanced solutions for Mobile Robots and Automated Guided Vehicles (AGVs). Consequently, intelligent production can be implemented even in areas where traditional cabling is either impractical or where configurations require rapid modification. This article analyses the potential of IoT within Industry 4.0, emphasizing the integration of tactile and wireless technologies to boost overall efficiency and productivity. The EU-funded iNGENIOUS project is presented as an exemplar of IoT implementation in a realistic industrial environment through its Factory Use Case (UC).

2. IOT APPLICATIONS FOR THE SUPPLY CHAIN

Supply chains are among the most dynamic and challenging components of modern business operations, demanding precise coordination and efficient cooperation across multiple logistical segments, processes, and entities. Within this framework, integrating IoT technologies and advanced data analysis solutions is becoming crucial for optimising operational performance. These intelligent systems facilitate the rapid identification of anomalies or bottlenecks and the real-time resolution of emerging problems. By enabling continuous monitoring and adaptation of work processes in factories, warehouses, transport, logistics, and maritime ports, these technologies enhance traceability, efficiency, and predictability throughout the entire supply chain.

2.1. Iot applications in smart factories and warehouses

By 2025, industrial manufacturing companies are predicted to implement smart factory solutions massively, based on Next-Generation IoT (NG-IoT). These solutions integrate sensors, M2M protocols, and cloud platforms to optimise every stage of the supply chain. It is estimated that there will be over 41 billion IoT devices globally, and operational efficiency will significantly improve due to the real-time collection and analysis of data. Key innovations brought by NG-IoT include connectivity with reliability greater than 99.999% for control and greater than 99.9% for detection. These systems achieve latencies below 10 ms and localization precision of $\leq 0.5\text{m}$, which are essential for critical industrial processes and asset management. The integration of IoT sensors with cloud management systems and AI modules leads to automated procedures for predictive maintenance, forecasting, and optimising logistical flows. Smart warehouse applications include predictive maintenance for equipment, high-performance monitoring of every logistical process, automated control of loads, connected logistics, asset management, and industrial safety. AGVs and mobile robots use advanced algorithms and navigation sensors, such as LiDAR, 3D cameras, and SLAM (Simultaneous Localisation and Mapping), to achieve flexible routes. This capability reduces fuel costs and accelerates product delivery. Warehouse management systems can assign optimal routes, and AGVs facilitate 24/7 operations with absolute precision, thereby optimising cargo flow and eliminating the risks associated with manual transport. Examples of industrial IoT applications include the MindSphere solution developed by Siemens, which is an Industrial IoT as a Service (IIoT-as-a-Service). MindSphere uses advanced analytics and AI to power edge-to-cloud IoT solutions, enabling factories and warehouses to visualize real-time data and analytical results in a centralized location without requiring proprietary development. Furthermore, Amazon Web IoT services combine cloud computing, machines, and analytics to enhance industrial productivity and performance. This module supports various use cases, such as predictive maintenance, predictive quality, and monitoring the status of assets.

3. TACTILE IOT APPLICATIONS

The Tactile Internet represents an advanced stage in the evolution of the Internet of Things (IoT), characterized by extremely low latency combined with high levels of reliability, security, and availability. Tactile IoT applications are specifically designed to execute tasks by continuously monitoring input data and making corresponding adjustments to the output data. These applications involve remote interactions between various entities—whether they are physical devices, humans, or even virtual entities—providing a user experience that mimics direct interaction. These interactions encompass the accessing, perception, manipulation, and control of objects or processes. They are distinguished by strict requirements for ultra-reliable and low-latency communication (URLLC) within 5G networks to ensure real-time perceived responses by users. Historically, IoT was associated with the implementation of simple devices like sensors or switches with relaxed synchronization requirements. However, the Tactile Internet broadens this scope to include a vast range of applications that impose strict end-to-end latencies and superior communication performance, opening new horizons for remote operations and digital interactions. In the recent period (2024–2025), tactile IoT applications have expanded significantly, fueled by the evolution of 5G networks and the massive implementation of URLLC platforms across sectors like industry, transport, medicine, and smart cities. Major developments include:

- Tele-surgery and tactile medicine: Physicians can perform remote operations with simulated direct touch and proprioception, benefiting from sub-millisecond data transmission and robotic control, which allows for instantaneous reaction and increased safety.
- Robotic control in industry: Operators can manipulate autonomous vehicles, utility machinery, or robots from outside the factory. Real-time visual and haptic feedback is guaranteed by 5G URLLC networks used in smart factories and logistics chains.
- Virtual and Augmented Reality (VR/AR): Tactile IoT platforms enable multi-sensorial control over mixed environments, which are used for industrial training, simulations, and digitally assisted maintenance, directly impacting safety and productivity.

Tactile IoT differs from traditional implementations through several key features: strict end-to-end latency requirements and ultra-rapid synchronisation; integration with AI and edge computing for local data processing, which reduces dependency on the cloud and increases response speed; and advanced communication security between physical and virtual entities, often utilizing DLT/blockchain for auditability and remote command management.

3.1. Tactile internet applications encountered in supply chain stages

IoT has the capacity to fundamentally transform supply chain operations through the integration of varied applications, such as predictive maintenance, smart stock management, and real-time response.

Real-time response scenarios typically fall into two main categories:

- **Human-in-loop:** Human operators interact remotely with physical or virtual objects, receiving multisensory feedback (visual, auditory, and haptic) to replicate a direct experience. Technologies utilized include haptic gloves, VR headsets, and hyperspectral imaging (HSI). These tools translate human actions into machine commands and machine feedback into signals perceived by the operator. This category specifically addresses the difficulties associated with transmitting kinesthetic movement and haptic touch over distance, alongside the strict synchronization needs in closed-loop control systems.
- **Machine-in-loop:** Machines, including actuators, sensors, and robots, are interconnected with computer-aided simulation models. This setup creates a realistic operating environment where digital identities are tightly connected, ensuring advanced synchronisation and performance.

These scenarios enable efficient human-machine collaboration, which is essential for modernizing logistical chains and boosting productivity through advanced IoT applications.

3.1.1. Teleoperation

Teleoperation allows a human user to operate a machine or device situated in a remote area. This is highly useful for performing tasks in inaccessible or dangerous environments, ensuring worker safety, and can also offer comfortable working conditions. Tactile teleoperation provides a realistic experience, making the user feel as though they are physically operating the remote device, unlike conventional remote control. In this architecture, one robot acts as the master, receiving commands from the operator and transmitting them to the remaining slave robots. The master and slave teleoperator devices exchange haptic signals, such as position, speed, forces, torques, and vibrations, in addition to audio and video signals via a Human-System Interface (HSI). HSI is responsible for encoding human actions into commands the teleoperator understands and translating the teleoperator's feedback into human-perceived signals. Recent platforms (2024–2025) use advanced haptic systems to transmit comprehensive tactile data. The modern teleoperation platforms implement multi-object control, allowing a single operator to manage several AGVs or robots simultaneously via a master-slave architecture, thereby increasing efficiency. Device-to-device (D2D) connectivity optimizes communication among robots in the same space, reducing centralized network traffic. A critical challenge is the communication bottleneck if the master robot fails, as all communication passes through it. To address this, current industrial platforms implement redundancy through fail-over protocols, automatic backup, and task transfer mechanisms to ensure robustness against operational and network errors.

3.1.2. Autonomous driving

Autonomous driving requires the processing of various types of information, including radar and optical images, generated by sensors installed on the vehicles or as part of the surrounding infrastructure. The detected data is transmitted to a controller, which must calculate and forward driving commands, such as acceleration, braking, and steering, within strict latency constraints. Autonomous driving also encompasses platooning, where the speed of a synchronized line of vehicles travelling in the same direction must be controlled. AGVs are an appealing option for the efficient transport of materials within warehouses and factories. However, current technology limits flexibility because the processing of sensor data and commands is often executed locally at the device level, rather than by a central control unit. To solve this, a common Application Programming Interface (API) that facilitates communication among AGVs, control units, and sensors is an attractive method for implementation. Autonomous platforms (2024–2025) use vehicles that instantly process data from LiDAR, optical sensors, 3D cameras, and radar. AI control algorithms ensure optimal steering and speed with latencies below 10 ms. Furthermore, edge computing enables local sensor data processing on the vehicle or factory infrastructure, increasing operational flexibility and reducing dependency on central servers. New autonomous driving platforms utilise industrial APIs that enable fleet management, real-time communication, and integration with Warehouse Management Systems (WMS).

3.1.3. Industrial automation

The industrial closed control loop necessitates URLLC requirements identical to those of the Tactile Internet. The first major application is the replacement of wired networks (e.g., EtherCAT, Profibus) with wireless solutions based on 5G and Time-Sensitive Networking (TSN). This transition results in superior flexibility for reconfiguring production lines, reduces maintenance and installation costs by up to 60%, and ensures reliable connectivity for mobile devices like

AGVs and cobots. The traditional Human-Machine Interface (HMI), consisting of a command terminal, screen, and monitoring software, is progressively being replaced by immersive platforms based on Virtual Reality (VR) or Augmented Reality (AR). These new interfaces allow operators to manage and monitor production lines remotely, offering instantaneous haptic and visual feedback. AR, for instance, enables the superimposing of real-time data onto the physical environment (e.g., maintenance instructions on equipment). This wireless transition has stimulated new paradigms in industrial automation, integrating digital systems, physical objects, and humans into a cohesive interconnected ecosystem. Flexible tactile automation sees fixed robotic arms being supplemented or replaced by programmable mobile robots and AGVs capable of executing a wide array of tasks, thereby increasing resource utilization in factories and optimizing logistic processes. Next-generation industrial platforms (2025) rely on 5G/6G industrial wireless networks to replace cabling constraints.

4. INDUSTRIAL AND TACTILE APPLICATION PROGRAMMING INTERFACE (API)

In the emerging context of Industry 4.0, future factories are envisioned as flexible, efficient, dynamic, and self-organizing entities capable of providing personalized products at scale (mass customization), moving away from traditional mass production. This transformation mandates the rapid reconfiguration of production lines and the establishment of dynamic, adaptable networks that connect digital and physical machines and people across real and virtual environments.

Consequently, the factory infrastructure—comprising network resources, edge nodes, actuators, and sensors—evolves into a ubiquitous computing platform designed to execute personalized applications in real time. These applications combine:

- Tactile (critical) processes: Requiring URLLC, such as haptic control, autonomous AGV driving, and teleoperation, with targets of less than 1 ms latency and 99.99999% reliability.
- Non-tactile processes: Requiring massive Machine Type Communication (mMTC) or enhanced Mobile Broadband (eMBB), such as reporting, predictive maintenance, and monitoring, demanding flexibility and high data volume.

Aligned with the Tactile Internet concept—which aims to provide a seamless experience when interacting with remote objects as if they were directly accessible—tactile applications require similarities in the programming of distributed remote terminals, mirroring the programming environment of a single computer. The network orchestration functions as the system's operating system, exposing APIs that abstract the underlying hardware and provide the necessary programming tools for software developers. The industrial and tactile API is a conceptual software abstraction crucial for implementing flexible production techniques. It is defined as a set of functions that allows application developers to securely and easily exchange data into and out of the system within a unified framework. This API must provide different abstraction levels to fulfill its purpose effectively. Specifically, three levels are identified:

1. End-user application development API: Offers a simple, intuitive graphical interface for visualizing data and instantiating new applications.
2. Mid-level function library: Contains specialized functions, such as object detection algorithms, that are not intended for direct use by the end-user.
3. Low-level API: Contains essential functions for specifying physical communication parameters based on user requirements and formatting data packets. These functions are fundamental for ensuring adequate data transfer and communication, particularly for systems requiring critical reliability and latency.

In the Industry 4.0 paradigm, tactile and industrial APIs are becoming the central pillar of smart factories, enabling process integration, connectivity, and the customization of operational flows.

4.1. Proof of concept within the ingenIOUS project

To validate the concept within the iNGENIOUS project, the integration between a non-3GPP radio access technology (e.g., LoRa, Wi-Fi 6E) and a Network Orchestration and Management (MANO) platform was achieved using the JavaScript Object Notation (JSON) format. JSON is a universal, open, and lightweight standard for structured data exchange, serving as the de facto standard for RESTful APIs due to its high readability, efficiency, and interoperability. In the iNGENIOUS architecture, MANO dynamically generates and transmits a JSON file detailing the resource

allocation for each application. The radio controller subsequently parses this JSON file and configures the corresponding 5G slice (e.g., eMBB for video streaming, URLLC for AGV control). The project developed an end-to-end (E2E) platform for the remote control of AGVs in a port environment. The primary motivation was enhancing driver safety by preventing exposure to hazardous industrial situations. The designed IoT system ensures continuous situational awareness regarding the vehicle's status and surrounding environment, enabling real-time communication of necessary control signals to safely operate the AGV. Exemplary API functionalities identified for AGV control include: starting, stopping, and adjusting the AGV's speed; transferring telemetry, position, and measurements to the end-user; capturing image frames and storing them in the user's database; and translating MANO resource allocations into Physical layer (PHY) parameters for the devices. The system uses rapid UDP connections dedicated to both the AGV and its integrated camera. The Factory UC defined an inspection application where an AGV moves along a predefined track with integrated camera and sensors, transmitting video and environmental data to a remote user who monitors the factory location.

5. CONCLUSION

This article analysed the disruptive potential of the Tactile Internet in industrial communications, demonstrating its capacity to offer real-time wireless control and manipulation through haptic and kinesthetic feedback. The successful operation of the Tactile Internet, as showcased by the iNGENIOUS project, fundamentally requires:

- Standardized interfaces (APIs) for device-machine-network communication.
- Programmable access to network resources (dynamic Quality of Service and network slicing).

This essential abstraction of both the network and hardware transforms the factory into a highly complex, yet intuitively programmable, distributed computing platform. The benefits of this transition are clear: a radical simplification of legacy architectures by eliminating rigid cables; guaranteed safe remote operation in hazardous environments (e.g., industrial tele-surgery); and horizontal scalability to accommodate new use cases, such as autonomous AGVs and haptic cobots. The strategic verdict for 2025 confirms that 5G Release 18+, featuring native support for MEC, URLLC, and TSN, is the dominant technology for the large-scale implementation of the industrial Tactile Internet.

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