Reference Implementation Model (RIM) for the Remote Controlled Robotic Inspection Use Case

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[RIM RCRI]

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1. Introduction

1.1. Purpose

The Innovative Optical and Wireless Network Global Forum (IOWN GF) is expected to accelerate the development and commercial availability of its architecture and technology in a relatively short period. To accomplish this goal for IOWN architecture and technology development, the IOWN GF develops and evaluates Reference Implementation Models (RIMs), which realize attractive IOWN GF use cases. The RIMs are also helpful for identifying potential technical issues and further improving the IOWN architecture and technology specifications.

The RIM utilizes IOWN GF architecture and technology developed by the IOWN GF to describe an end-to-end system that pushes the limits of existing system performance and meets the requirements of target use cases.

This document also aims to demonstrate many benefits of IOWN GF architecture and technology over today's implementations. The RIM adopts the IOWN's latest architecture and technology and continues to evolve to achieve low-cost and low-power consumption for realizing a sustainable society.

1.2. Approach

The RIM for the target use case is developed using the following three procedures.

1. Select a target use case from the various use cases of IOWN GF.

2. Develop a Benchmark Model for the selected target use case, a defined way of evaluating implementation models by measuring chosen metrics.

3. Develop RIM for target use cases that yield the best evaluation results defined in the benchmark model.

The RIM is expected to evolve repeatedly and achieve lower cost and power consumption by adopting revised IOWN architecture and technology.

Section 2 details the Benchmark Model for the target use case. Section 3 describes the flows and workloads of data processing in the Benchmark Model. Section 4 explains several major technology gaps and issues between today's cloud-based implementations and use case requirements in the Benchmark Model for the target use case. Section 5 defines the initial RIM using IOWN architecture and technology. Section 6 concludes our first achievements and describes future studies.

1.3. Scope

IOWN GF has initiated the development of RIMs, with CPS Area Management Security Use Case (AM Security UC) included in Cyber-Physical System Use Case Release 1 [IOWN CPS UC] and others already entering the Proof of Concept stage. This document covers an additional initial study on another target use case, the Industry Management use case included in IOWN CPS UC, and presents a RIM for this purpose. Being the initial RIM, it only includes qualitative evaluation and provides sufficient information to potential conductors of partial PoCs. Currently, there is no quantitative evaluation yet. The plan is to upgrade later revisions of this document with quantitative analysis using feedback obtained from the initial PoCs.

The RIM in this document has been developed concerning Open APN [IOWN Open APN] and Data-Centric Infrastructure Functional Architecture [IOWN DCI], and Data Hub Functional Architecture [IOWN Data Hub], which were released in January 2022, as well as subsequent development on these architectures at the IOWN GF.

2. Benchmark Model

This section describes the Benchmark Model for the IM UC, which defines the Reference Case in Section 2.1 and Metrics and Evaluation Methods in Section 2.2.

2.1. Reference Case

This subsection develops a Reference Case for the IM UC. The Reference Case digs deeper into the target use case and defines the conditions for determining functional and non-functional requirements. Defining the Reference Case for the target use case aims to make it accurate to evaluate implementation models by measuring selected metrics in specific conditions.

This section describes the basic requirements for the Reference Case called Remote Controlled Robotic Inspection Use Case (RCRI)

2.1.1. Description

This reference case outlines the capabilities of a maintenance expert who can remotely control on-site robots to carry out essential procedures. These procedures include thorough inspections, parts replacement, and valve closure as if the expert was physically present at the plant site.

The advanced remote maintenance capabilities enabled by this use case bring numerous benefits to the plant industry. It allows maintenance experts to make the most efficient use of their resources. It also enables long-term plant operations to be carried out in a safer, quicker, and cost-effective manner. Furthermore, the highly interactive communication applications developed for this use case have a wide range of potential applications beyond the plant industry, including healthcare, education, and entertainment. Leveraging these applications can further accelerate and improve businesses in these fields.
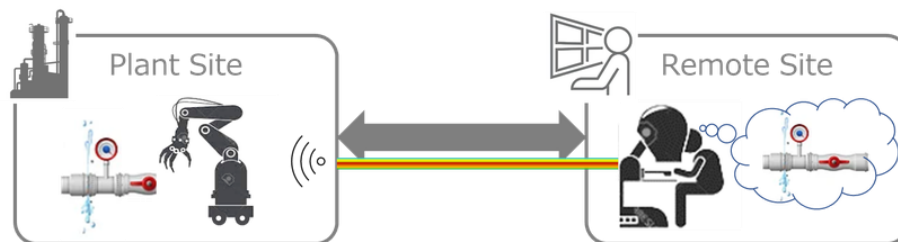
Figure 1. Overview of "Remote Controlled Robot Inspection"

2.1.2. Target Site

In this reference case, we aim to demonstrate that we can effectively identify and resolve problems in each typical petrochemical plant manufacturing process through remote operation. We also aim to verify that the system can maintain a stable communications environment even in harsh wireless environments such as steel pipes and steel structures, which negatively affect radio communications, especially at high frequencies such as the EHF band, and to clarify the feasibility of safely deploying multiple robots to perform inspection tasks even in such environments.

The plant site area in this reference case is 2 square kilometers, which was taken from the size of a typical plant in Japan. In addition, the distance between the plant site and the remote site was set at 1,000 km. Based on this RIM evaluation, future RIMs will consider long-distance cases, as actual businesses may have multiple ranges of needs, as shown below.

Figure 2. Distance between plant site and remote site

2.1.3. Device Types and Number

There are devices that capture streaming video/ sound/ and haptic information from the plant site and devices that present the information at the remote site.

- Remote Controlled Robots

  - Articulated robots or drones equipped with robot arms, cameras, microphones, and sensors at a plant site can be remotely operated by a maintenance expert from a remote location.

  - These robots can perform inspection and maintenance operations controlled through low-latency communication.

  - The attached cameras and microphones capture high-resolution video and audio streams (8K, 60FPS).

  - The robot arms are capable of capturing haptic information and executing precise maintenance tasks remotely, under the control of a maintenance expert at a remote site.

  - At the plant site, which is 2 square kilometers, there are 300 robots, with the capability to have 100 robots working simultaneously.

- Environmental Sensors

  - A group of sensors, including those for plant equipment, are installed at the plant site.

  - Some sensor data are collected through the plant's distributed control system (DCS).

  - Most of the remaining sensor data are collected by the wireless network.

- Presentation Devices

  - Devices that display the remotely collected information at the remote site, as shown in Figure 3.

  - Up to 20 presentation devices with the following set of features.

    - A Head-mounted display (HMD) equipped with VR/AR glasses and speakers, or a non-head-mounted large display set that provides an equivalent level of usability.

    - Haptic globes are capable of transmitting remote control input operations and feedback.

      - They receive haptic information from the plant site and present accurately with low latency enough to perform tasks such as retightening valves. By synchronizing the

operation of the maintenance expert at the remote site with the robot at the plant site at low latency, the expert can perform maintenance such as valve opening and closing and parts replacement.

- Note

    o   Up to 20 remote operators (inspection experts) may monitor at the same time.

    o   An operator can operate 5 robots in parallel while switching targets.

    o   Each robot can be remotely operated by only 1 operator.

Figure 3. Presentation device

2.1.4. Captured Data

The following data is captured by remote-controlled robots via wireless networks.

- Video and audio stream data

    o   A robot with a video camera and microphone captures high-resolution video at 8K 60 fps with audio and transmits it to the remote site.

- Haptic data

    o   The robot arm sends haptic information to the remote site when it interacts with equipment.

- 3D location data

    o   Accurate 3D position data on robot position and surrounding information: integrates robot position data with Building Information Modeling (BIM) data in the surrounding area.

The following data is captured by environmental sensors via wired or wireless networks.

- Sensor data

    o   Sensors installed at the facility transmit temperature, pressure, vibration, and gas leak data for specific inspection points.

2.1.5. Presented Data

- The remote operator can view the real-time video and audio streams through a presentation device.

- The operator can view the precise 3D position of the robot in real-time by combining the BIM data with the captured streaming data.

- The haptic glove worn by the remote operator replicates the information that the robot is touching in real-time.

- It would be best if real-time video data could be combined with sensor data and BIM data and presented as a 3D image for VR/AR. However, considering the delay in video generation, we have not made this an essential part of this reference case.

2.1.6. Remote Control Data

- Control signals for movement and posture control for real-time remote control of robots and robot arms on the plant site, feedback signals for control results, and tactile data from haptics sensors.

2.1.7. Requirements

The following requirements are required for the remote inspection in this reference case.

- Data reference aspect

  - The remote operator can compare the current data with past data from previous inspections.

  - Video/audio/haptics can be referenced for inspection locations against BIM information.

  - Recording and sharing of operation videos: The operator can share specific operation videos and sounds with other inspectors or supervisors and record videos and sounds as a record for future diagnosis.

- Robot operation

  - The remote operator can see 6 DoF (degree of freedom) footage away from the remote site. The robot in the plant works synchronously according to the input of the remote operator.

  - Accurate 3D positioning of robots: The robot must have the ability to accurately determine its position and orientation with an error of less than 5 cm relative to the site map shown in BIM.

  - The robot must be able to perform the following operations based on the remote operator's actions.

    - Level 1: Simple operations (e.g., fasten screws, bolts, and nuts, operate buttons, etc.)

    - Level 2: Operations requiring tactile feedback (e.g., valve operation, hammer-sounding inspection)

    - Level 3: Operations requiring a high degree of freedom (e.g., defective or damaged parts replacement, etc.)

- Network aspects

  - Ideally, to achieve the above remote control of the robot, the time from the remote inspector's input to the robot's actual movement needs to be 10 ms or less. However, since 1,000 km communication by itself causes a 5 ms latency due to optical transmission, the total latency must be as small as practically feasible with IOWN. In this RIM, realistically acceptable delays are defined for each type of communication as shown in figure 4: 100 ms for the delay related to the display of video from robots, 100 ms for the delay related to input operations to a robot, and 10 ms for feedback (e.g., tactile feedback) from robot operations.

  - The reliability (message reachability guarantee) required for critical robot control signals will be 99.999%.

  - Reliability of wireless networks: The system must have the ability to allocate the necessary network resources for optimal performance on local wireless networks.
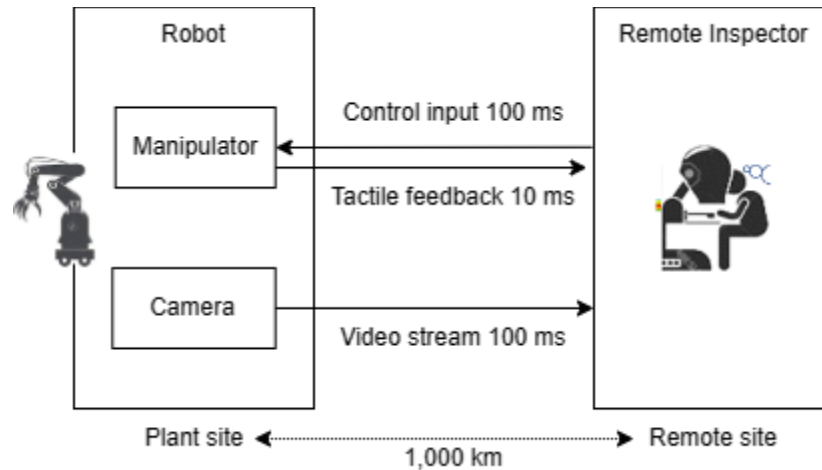
Figure 4. Latency diagram in RCRI

2.2. Metrics and Evaluation Method

This subsection describes the metrics and evaluation method for the Reference Case.

2.2.1. 2.2.1. Metrics

The first metric is the cost of conducting inspections. The cost includes the system cost of installing RCRI, communication and operating cost, human resources cost of local workers and inspection experts, and travel costs of the experts.

The next point of evaluation is the change in operating time due to RCRI. Operating time includes the number of hours of operation per facility, the number of operations per day, the time it takes to find a problem, and the time to resolve the problem.

Another major point is the improvement of safety through RCRI. Overall, the number of work items with hazards that could be accomplished by remote inspection is an indicator.

2.2.2. Evaluation Method

The RCRI RIM will be evaluated by comparing the above metrics with the following current technology realizations.

1.   Current on-site operations without any remote-controlled robots.

2.   4G/5G + Internet-based remote robot operations.

3.   Dataflow and Workloads Analysis

In this section, we first analyze the data processing flows of the benchmark model. In addition to the key requirements listed in the use case document, we aim to identify broader requirements for system design. This section then breaks down the data process into sub-processes and defines the behavior of each sub-process. Finally, this document clarifies the connections and data flows between subprocesses until they are granular enough to be evaluated in the context of the technology that IOWN GF is studying. Through this analysis, we leverage the Dataflow and Workload Profiling framework developed by IOWN GF to identify service gaps/requirements accurately and efficiently for use cases. A more detailed analysis is described in Appendix -1. For more information about this framework of the analysis, see Annex B of the Reference Implementation Model (RIM) for the Area Management Security use case [IOWN GF CPS RIM].

3.1. Data Pipeline Diagram

Figure 5 shows the Data Pipeline Diagram (DPD) for the RCRI UC to analyze the data processing and data flow.
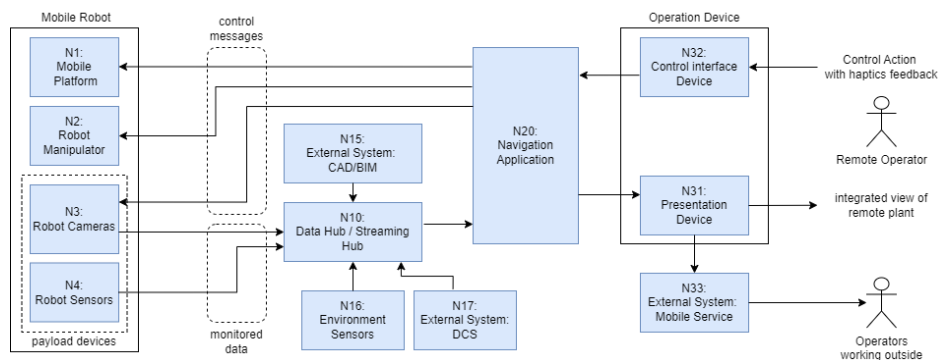
Figure 5. Data pipeline diagram of remote-controlled robotic inspection

As shown in the diagram, it has the following functional nodes:

- Mobile Robot

    - Robots should be remotely controlled with latency as defined in section 2.1.7, which allows seamless communication between robots and remote operators at a distance of 1,000 km. One remote operator will watch 20 video streams.

    - There are two types of communications: one for controlling the robot itself, manipulators, and sensors ("control messages"), and the other for output of inspection such as video stream or sensor data ("monitored data").

- N1: Mobile platform

    - Articulated robots capable of moving through the plant as instructed by N20 navigation application. They can carry multiple manipulators and sensors, such as N2 Robot manipulators, N3 Robot cameras, and N4 Robot sensors.

    - It receives control messages from N20 Navigation Application and sends responses to N20.

- N2: Robot manipulators

- o Manipulators attached to N1 Mobile platform can do the following remote operations with haptic feedback as instructed by N20 navigation application.

- o It receives control messages from N20 Navigation Application and sends responses to N20.

- N3: Robot cameras for inspection

  - o Devices that capture streaming video and audio for remote inspection. Attached to N1 mobile platform.

  - o N3 consists of multiple cameras and microphones and captures multiple video and audio streams using the following devices.

  - o It receives control messages from N20 Navigation Application and sends responses to N20.

  - o It sends selected streams of video and audio data to N10 Data Hub / Streaming Hub.

- N4: Robot sensors

  - o Devices for sensing monitoring information on the inspected object and the surrounding environment. Attached to N1 Mobile platform.

  - o It sends monitored data to N10 Data Hub / Streaming Hub.

- N10: Data Hub / Streaming Hub

  - o A hub node to manage and store all the necessary data for remote inspection and relay it to the application.

  - o It receives one or multiple video and audio streams from N3 and multiple sensor data from N4 and relays them to N20 Navigation Application.

- N15: External System: CAD/BIM

  - o An external system node that stores CAD/BIM data, such as 3D maps of the plant, and design information, such as the location and geometry of equipment and corridors.

  - o It sends CAD/BIM data to N10 Data Hub / Streaming Hub.

- N16: Environmental Sensors

  - o Additional sensors are attached to facilities such as the followings.

  - o It sends sensor data to N10 Data Hub / Streaming Hub.

- N17: External System: DCS

  - o An external system called DCS (distributed control system) is a standard control system in a process plant in which sensors and autonomous controllers are installed in essential equipment throughout the plant.

- N20: Navigation Application

  - o An application that integrates information from cameras, CAD/BIM data, sensors, etc., and renders real-time 3D video with audio and sensor data, as well as enabling remote robot navigation and remote control through instructions for areas requiring detailed investigation.

- o It gathers monitored data from N10 Data Hub / Streaming Hub, integrates them, and sends integrated data to N31 Presentation device.

  - o It also receives control commands from N32 Control interface device and sends control messages to N1/N2/N3 and receives their response.

- N31: Presentation device

  - o HMD devise with VR or AR glasses with speakers (optionally multiple large screen displays with speakers) that present a video/audio stream of a remotely controlled field of view (target object).

  - o It receives integrated presentation data from N20 Navigation Application and shows it to a remote operator.

- N32: Control interface device

  - o User interface device for remote control of robots. It consists of a general user interface to navigate and control a remote robot. (e.g., HMD controller, gamepad, etc.) and haptics globes which receive haptics feedback from the plant site and present accurately with low latency.

  - o It receives user input from a remote operator and sends control commands to N20 Navigation Application, with haptics feedback sent in the opposite direction.

- N33: External System: Mobile Service

  - o An external system that allows a supervisor outside of the remote site, such as at home, to be notified of the status of a remote inspection and to request assistance.

  - o It receives information on remote inspection application screens from N31 presentation devices.

3.2. Dataflow Profiles

In this subsection, we show which of the data flow profiles are of particular importance to this RIM and could potentially be design bottlenecks. Each data flow profile includes a specific data type derived from the DPDs to support a given benchmark model. The following DPDs have shown that different types of data need to be handled differently. Each data type has individual data flow requirements (number of sources, data rate, data size, occurrence rate, etc.).

3.2.1. Remote Control and Haptics Feedback for Remote Manipulating

As described in A 1.3.2 N2 Robot manipulator, the following profiles are required for communication for remote operations of Robot manipulators (N2). In the following table, N2-I1 refers to the communication from the Navigation application (N20) to a Robot manipulator (N2), and N2-O1 refers to the communication from N2 to N20, respectively.

ID	DESCRIPTION	ATTRIBUTES

ID	DESCRIPTION	ATTRIBUTES
N2-I1	• Manipulator control commands	• # of sources: one per a robot • Data size: 200 B / message • Occurrence rate: 500 messages / sec • Latency: 100 ms • 1 Mbps at the maximum • Reliability: 99.999%
N2-O1	• Manipulator feedback including haptics information	• # of sources: one per a robot • Data size: 48 B / message • Occurrence rate: 500 messages / sec (with compression) • 200 kbps at the maximum (per a robot) • Latency: 10 ms • Reliability: 99.999% • (Ref. "*Teleoperation*" use case analysis from IEEE 1918.1 "Tactile Internet")

3.2.2. Video and Audio Streams from Remote Robots

As described in A-1.3.3 N3 Robot camera, the following profiles are required for communication for collecting data from Robot cameras (N3). In the following table, N3-O1 refers to the communication from a Robot camera (N3) to a Data Hub / Streaming Hub (N10).

ID	DESCRIPTION	ATTRIBUTES

N3-O1	• Selected streams of video and audio data o High-definition camera: uncompressed 8 K 60 fps (about 48 ~ 72 Gbps without compression) o 3D (stereo or depth) camera: 4K o Manipulator close-up camera: 4K o Infrared camera: 4K o X-ray camera: 4K o High precision microphone: 96kHz x 24bit x 2 channel (4.6 Mbps)	• # of sources: Up to 5 cameras and 1 microphone per a robot • Data size: see the left column for each stream • Bitrate: Up to 2.5 Gbps for multiple streams combined assuming JPEG XS compression. • Latency: 100 ms • Reliability: o Video for operation: 99.999% (As frame drop rate. However, it is desirable to guarantee a maximum video interruption time, which is targeted at 0.1 second.) o Video for inspection: 99.9%

3.2.3. Aggregated Data Flow via a Data Hub / Streaming Hub

As described in A 1.3.5 N10 Data hub / Streaming hub, the following profiles are required for communication for aggregated data flow. In the following table, N10-I1 and N10-I2 refer to the communication from Robot cameras (N3) and Robot sensors (N4) to a Data Hub / Streaming Hub (N10), and N10-O1 and N10-O2 refer to the communication from N10 to Navigation application (N20).

ID	DESCRIPTION	ATTRIBUTES
N10-I1	• Video and audio stream data	• # of sources: 100 robots • Bitrate: Up to 2.5 Gbps for multiple streams combined per a robot • Total Bitrate: 250 Gbps
N10-I2	• Sensor data from robots	• # of sources: 100 • Bitrate: Up to 100 Mbps for multiple sensors combined • Total Bit rate: 10 Gbps
N10-O1	• Video and audio stream data	• # of sources: up to 20 (remote operators) • Bitrate: Up to 50 Gbps
N10-O2	• Selected data based on queries	• # of sources: up to 20 (remote operators) • Bitrate: Up to 2 Gbps

4. Technology Gaps and Issues

4.1. Unpredictable Network Constrains Capacity, Latency, and Reliability of Communications

In RCRI, large amounts of video and sensor data from the robot are sent to a remote site 1,000 km away. However, as with normal Internet long-distance transmissions, the network has unstable communications bandwidth, making remote operation using video impossible during network congestion. In addition, the most severe delay (the case of haptic feedback) allowed is 10ms. About 5 ms of the latency budget is already taken by the light speed delay (10 ms latency over 1,000 km), therefor the remaining budget is 5 ms, including wireless communication, which is expected to have a delay of about 1 ms, and application-level processing. However, such a low end-to-end delay cannot be guaranteed in networks where the delay is so large that jitter cannot be guaranteed. In addition, current technology uses many techniques at higher layers to guarantee network uncertainty, but all of them require additional performance costs, such as latency caused by buffers, etc. To meet the reliability requirements of this case, fundamentally stable network performance is required.

4.2. Inability to Achieve Both High Reliability and Low Latency in End-to-End Communications

The RCRI requires end-to-end ultra-reliable and low-latency communication that ensures reliable and safe remote operation of robots deployed 1,000 km away from operators. However, reliability and latency are trade-offs in current standard protocols. With today's common Internet protocols, end-to-end message delivery guarantees are ultimately the responsibility of the application level. Therefore, messages must be waited for with timeouts set at the application protocol level, resulting in delays. To realize high reachability guarantees, longer delays need to be implemented. Application-level buffering and message serialization also cause delays.

4.3. Lack of Adequate Methods for Streaming Large Volumes of High-Definition Video with Low-Latency

Also, in this reference case, large amounts of data from cameras and sensors mounted on the robot must be reliably recorded in a data streaming hub. At the same time, the video images being referenced by the remote operator for robot operation must be relayed to the remote location with a 100 ms delay. However, the data capacity is 72 Gbps per robot when uncompressed, and it is currently difficult to achieve both this large capacity and low latency.

4.4. Instability of Wireless Coverage Area

To communicate with a freely moving robot, the last hop of communication must be wireless. However, industrial environments are extremely harsh for wireless communications. Complex steel pipe crossings in a chemical plant, for example, can impact wireless network performance significantly. It is difficult to guarantee stable communications with existing wireless network technology due to the effects of radio wave shielding, reflections, and so on. As a result, in the area of the plant to be inspected, there are deficient areas where the network performance required for the transfer of video and sensor data cannot be guaranteed. Furthermore, in this reference case, the disruption of communication with the robot can lead to robot malfunctions, which can lead to serious accidents in chemical plants. Generally, low-frequency band radios can be used to cover the wireless communication area, but since high-definition video communications at the Gbps level are required in this RIM, low-frequency bands do not provide the necessary communication bandwidth. Therefore, a technology that can both guarantee wireless area coverage and high bandwidth communication even in harsh environments is desired.

4.5. Operational limitation Due to Network Boundary Protection for Security

In plant systems, the confidentiality of data related to operations is extremely important. In particular, DCS and BIM data must be kept highly confidential because the information is linked to manufacturing methods and other intellectual property that are central to a company's competitiveness. In addition, if the DCS is hijacked or malware is introduced, it could cause extensive damage, including large-scale accidents and environmental impact in the surrounding area.

For these reasons, to meet the requirements of several international standards, on-premise systems are operated as private networks isolated from the Internet and the company IT network. This is based on the classic idea that security is improved by separating it from other networks and building strong border protections. However, this RIM requires the sharing of sensitive video and sensor data not only within the local site but also between multiple sites. This requires secure communication channels between the two sites with appropriate permissions for remote data access, although the cost of providing the high-capacity, secure leased lines required by RCRI is significant with current technology. Other approaches, such as VPNs, where the communications protocol is layered on top of IP Sec or TLS protected by advanced encryption, also cannot handle the sheer volume of data (250 Gbps) in the current technology implementation.

To address these concerns, the network and data hub service in this RIM should provide high data security capable of protecting sensitive data beyond current industry standard practices.

5.   Initial Reference Implementation Model:

This section illustrates a first reference implementation model (RIM) for the given benchmark model using the IOWN GF architecture and technology. In Section 3, we analyzed which functional nodes are required for the given benchmark model and how much traffic needs to be transferred throughout the system. In Section 4, we also identified several significant technology gaps and issues in today's technologies. In this section, 5.1 presents the basic strategy for addressing these issues using IOWN technology. Then, 5.2 and 5.3 describe a concrete design of a geographically distributed data pipeline and its functional nodes for this use case. Finally, 5.4 explains the expected benefits of the IOWN GF RIM.

5.1. Basic strategy of The Architecture and Design

The RCRI requires a highly reliable and high-capacity infrastructure as well as enhanced security, as described in section 4. This subsection briefly revisits and summarizes each of these issues and highlights how the IOWN Overall Architecture and its high-level components will overcome the issues of today's technology for realizing the RCRI.

5.1.1. Deterministic Quality Networking

RCRI requires communication links with guaranteed quality of service with respect to bandwidth, latency, and reliability between nodes for low latency transmission of large volumes of data, such as high-definition video and sensor data from remote robots. However, current technology provides neither a standardized nor cost-effective method for establishing such high QoS links over long distances.

As noted in the AM Security UC RIM, IOWN Overall Architecture's Infrastructure Orchestrator provides seamless management of geographically distributed deployments through integration with DCI and its integration with Open APN, which enables automated provisioning of Function-Dedicated Networks (FDNs), an end-to-end path with guaranteed quality of service across multiple network segments over long distances. In RCRI, this orchestrator also provides a solution to the problem of enabling the transfer of very large volumes of data.

5.1.2. Communication Stack that Enables Reliable and Low Latency Messaging.

As explained in section 4.2, with the current protocols built on unpredictable networks, it is inevitable that a certain amount of delay is due to buffering and message serialization at the application level. To resolve this, IOWN defines a way to communicate that goes beyond existing trade-offs. The DCI functional architecture document [IOWN DCI] describes DMA/RDMA-based protocols that enable hardware offloading, which contribute to possible link utilization, energy efficiency, and latency reduction. Hardware-based RDMA messaging based on APN-based reachability guarantees eliminates the need for application-level reachability guarantees, resulting in high reliability with low latency.

5.1.3. Hardware-Based Data Transfer with Adaptive Video Encoding

The hardware-based data transfer that is adopted in AM Security UC RIM can also be used to reduce latency when transferring large amounts of data. This method uses an RDMA-based transfer protocol to reduce data copying between nodes, achieving low latency and low power consumption at the same time.

In addition, in this RIM, the only video transmission that requires low latency of 100ms is the video that the remote operator is watching. For the rest of the video, normal high-compression encoding can be used. By dynamically switching the encoding according to the video being viewed by the remote operator, both effective use of bandwidth and low latency can be achieved.

5.1.4. Guaranteed Wireless Coverage Through Multipath Utilization and Wireless Link Quality Prediction

When considering end-to-end reliability and volumetric data transfer, ensuring the quality of wireless communications is also very important. In particular, the robot to be operated moves through a plant with a complex array of iron pipes and other structures, making the environment extremely difficult for wireless communications, such as the reflection of radio waves.

We can provide wireless communication technology that uses multiple wireless links to ensure packet reachability and guarantees a certain level of reliability and bandwidth through wireless communication quality prediction technology by measuring physical space information.

5.1.5. Expanding the Security Boundaries with Zero-Trust Protection and Strong Cryptography

As described above, the network and data store in this RIM should provide high data security capable of protecting sensitive data beyond current industry standard practices while allowing for secure operation from a remote operation site. To this end, this RIM will implement mechanisms to ensure that data managed by the system is stored securely and that data transfer to remote locations is protected by strong security while ensuring strict access control in the following ways:

- Zero-trust protection for accessing stored streamed data

- Automatic and highly secure encryption for stored data in the data hub

- Post-quantum protection of data in transit between sites using encrypted secure transport with multi-factor security [IOWN Security].

5.2. Geographically Distributed Data Pipeline
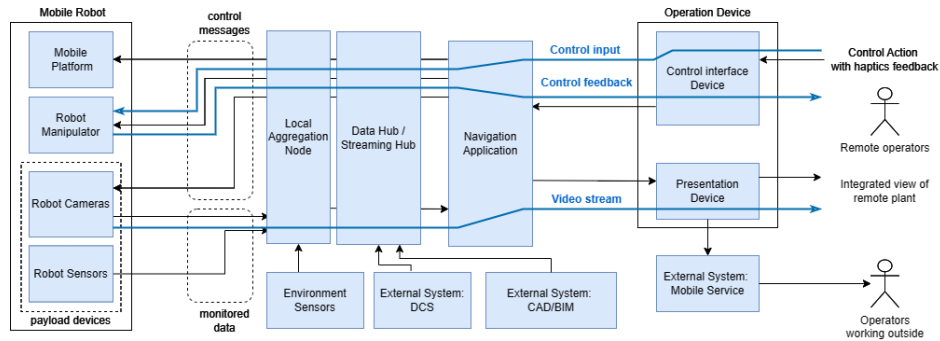
Figure 6. Application view of Remote Controlled Robotic Inspection initial RIM
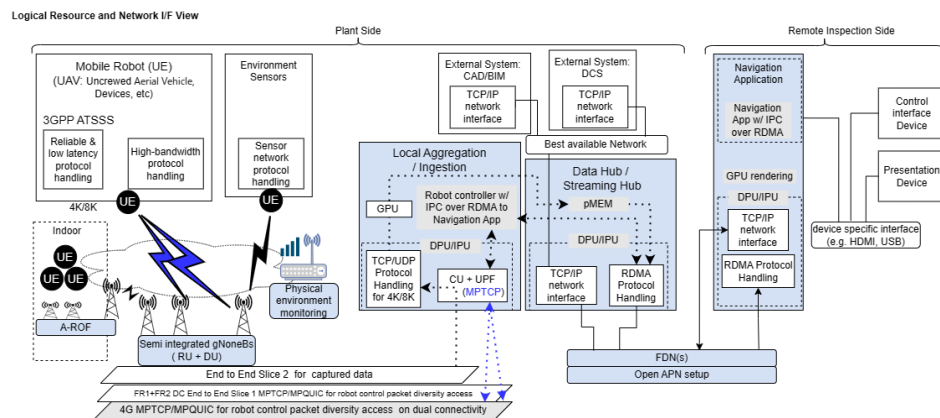
Figure 7. Logical Resource and Network I/F View

Figures 6 and 7 provide an overview of the initial form of the IOWN-based RIM. This RIM employs optimized communication methods utilizing IOWN technologies such as Open APN and DCI (RDMA) to address the technical gaps described above. For an in-plant wireless network, IOWN uses the local 5G-based disaggregated RAN architecture discussed in the IOWN for Mobile Network [IOWN IMN], plus technology to ensure local wireless coverage by measuring the physical environment. In addition, IOWN security technology is used to secure data managed and transferred within and between plants, enabling secure data access from remote locations, even in use cases where confidentiality is particularly high. Combined, this RIM enables efficient plant maintenance from a distance, something that has been difficult with existing technology.

5.3. Initial Design for Each Functional Node

5.3.1. Mobile Robot (UE) and Wireless Network

As an example, when a 5G RAN is deployed in the customer plant site, the multiple semi-integrated gNB (RU+DU) or IAB node (DU+MT) are deployed in each coverage area where UE of Mobile Robot (UAV: Uncrewed Aerial Vehicles/Drone) and UE of Sensor working. CU is deployed in the managed DCI system together with UPF. This will be a benefit for the Mobile Robot, which will have a noticeable quality of experience and mobile efficiency if compared with fully integrated gNB (RU+DU+CU), as packet transaction is reduced within the broader CU coverage footprint at the handover phase as the same anchor (i.e., the same CU and UPF) helps to reduce transactions.

And each UE of the Mobile robot will support a reliable protocol such as ATSSS (Access Traffic Steering, Switching, and Splitting) to connect to UPF running MPTCP/MPQUIC proxy function that can solve problems such as packet loss

while maintaining compatibility with existing protocols by using multiple radio links. The UPF running in DPU/IPU will need to support MPTCP/MPQUIC proxy, and the Mobile robot controller app, such as the UAV controller, will run IPC over RDMA by the remote Navigation application. This implementation helps to increase command & control packet speed between the Mobile robot and remote inspection site via the Local aggregation node. The Mobile robot also will monitor a specific area and transfer the captured data via a specific network slice to UPF, connecting DPU/IPU that decouples the protocol header and stores the payload data in GPU memory.
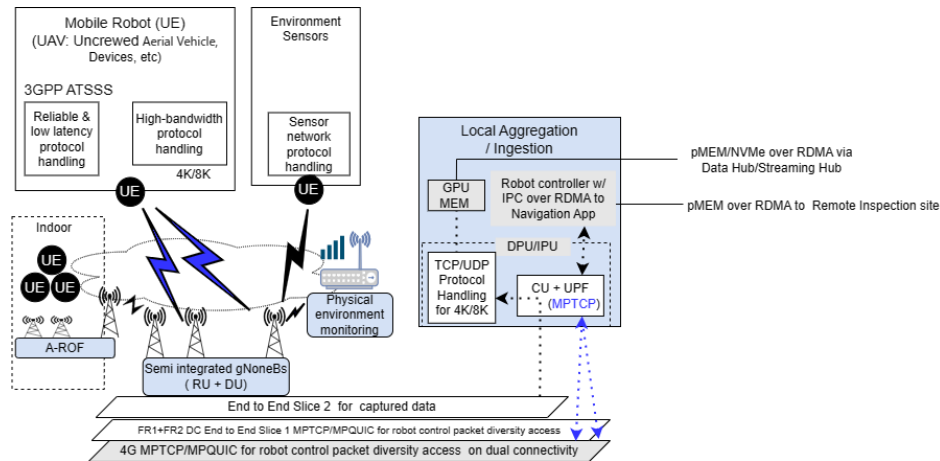
Figure 8. Initial RIM for Mobile Robot and wireless network

If the physical space information and wireless communication information in the plant are measured simultaneously, the measured physical space data set can be used to predict future wireless link quality and communication performance. While fixed sensors could be distributed and used for such measurements, it is also possible to measure a wide range of environmental data by moving the UEs autonomously.

For the video feed that operators need to monitor, it needs to be transmitted with very low latency. However, sending low-latency uncompressed video for all cameras would result in huge wireless bandwidth utilization. So, the mobile robot can switch the encoding methods of a video stream to send on an individual basis. This is done via instructions from the Navigation application. The video stream currently being viewed by the remote inspector is transmitted in low latency video encoding (such as JPEG XS) since very low latency is required. For video data other than that currently being viewed, HEVC or VVC encoding is used to transmit the video data to save wireless bandwidth. In both cases, the video data is packetized in RTP or RTSP and sent to the local aggregation node with the aforementioned reliable radio protocol.

5.3.2. Local Aggregation Node

Local aggregation nodes are installed at the plant site and aggregate local wireless communications within the plant, aggregate video and sensor data and send it to a data hub/streaming hub at the same site, and relay control communications between the mobile robot and navigation. It also relays control communication between the mobile robot and the navigation application. For this purpose, DPU/IPU is used to convert between the protocol used in the wireless section and the Open APN protocol, ensuring total reliability, including communication capacity and low latency.

- The DPU/IPU processes the conversion between reliable protocols such as ATSSS and Open APN's RDMA-based protocols deployed in the local wireless network, using a highly reliable wireless network I/F (CU + UPF) with MPTCP, etc.

- The data received by the DPU/IPU is placed into the shared memory, which is then shared with the Data Hub / Streaming Hub in the same DCI cluster.

- The DPU/IPU or GPU function deploys the data to persistent memory (pMEM) in the Data Hub / Streaming Hub.
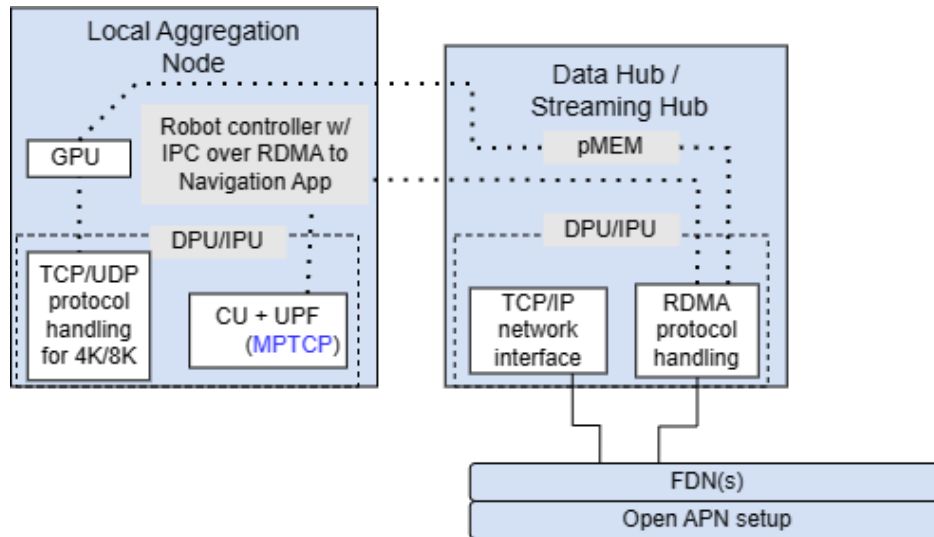

Figure 9. Initial RIM for Local Aggregation Node and Data hub / Streaming Hub

5.3.3. Data Hub/Streaming Hub

The Data Hub implements the following features. The ability to transfer streaming video via DPU/IPUs over FDN and Open APN, either highly compressed encoded video or low latency encoded video, to the Remote site. This communication will utilize the RDMA-based communication protocols for video transfer that are proposed in RIM AM Security. It utilizes the latest data plane acceleration technologies (e.g., reduced memory copy, DMA/RDMA-based data transfer protocols) together with the DCI architecture. These protocols can streamline redundant data flows and reduce latency caused by extra data copies. Data transfer between DCI clusters is accomplished by utilizing RDMA-based data transfer between FDN interface cards. The sender sends the data by pushing it into the shared memory of the FDN interface, and the receiver reads the data from the shared memory and maps it to the processor for processing. This process is done without involving the CPU on the host board, enabling faster processing than conventional data-on-transfer protocols. The shared data is stored in pMEM (persistent memory), which is implemented as a storage tier of the data hub. This allows the service tier of the data hub to directly retrieve the stored data to the data requester without requiring a large data transformation or copy.

Video data sent from the mobile robots via the local aggregation node and sensor data collected from CAD/BIM and DCS will be stored in the Data hub using encryption with strength suitable for long-term storage and resistance to data leakage. Data transferred to the Remote Site will be transferred in quantum-resistant encryption through the APN transport, and deployment of decrypted data is limited to within the Navigation application node only, as described in the next section. This fulfills the high-security requirements needed by this reference case.

5.3.4. Navigation Application Node

The navigation application node is implemented on DCI architecture, and it receives the video and sensor data received from the APN. The video and sensor data are then rendered to form the operating screen of the remote operator and sent to the presentation device via a device-specific interface (e.g., HDMI). It also receives user input from the Control interface device and sends those instructions as control messages through the APN. RDMA-based data transfer protocols are used for the former communication, and RDMA-based IPC messaging protocols described in section 5.3.1 are used for the latter communication.

Data in application nodes configured in a DCI cluster is copied from the DPU/IPU to the GPU memory by DMA mapping and sent directly to the presentation device by rendering in the GPU process. This configuration significantly reduces delays caused by CPU copying data between processes and delays caused by shaping and serialization of data frames.

From a security standpoint, long-distance communication between the Data hub/Streaming Hub and Navigation Application Node is built on top of the Open APN and is protected by MFS (Multi-Factor Security) of IOWN Security. Thus, it provides better resistance to external attacks than existing VPNs and leased lines. In addition, by constantly monitoring the user's status in the Application Node in real-time, taking into account the user's login status to the application, for example, as well as the wearing status of the user interface device such as HMD, the system can be used to determine when a legitimate access source is connected. Data is transferred from the Data Hub / Streaming Hub only when a legitimate access source is connected. As explained earlier, video data and other data required for the application are rendered via a memory share within the DCI cluster and presented directly to the presentation device. During this time, data is not stored on disk or made accessible to external processes outside the DCI cluster via TCP/IP inter-process communication. Thus, confidential video and sensor data are guaranteed to remain decrypted only within the DCI cluster and presentation device. Past data cannot be stolen from the Navigation Application Node because it disappears from memory.
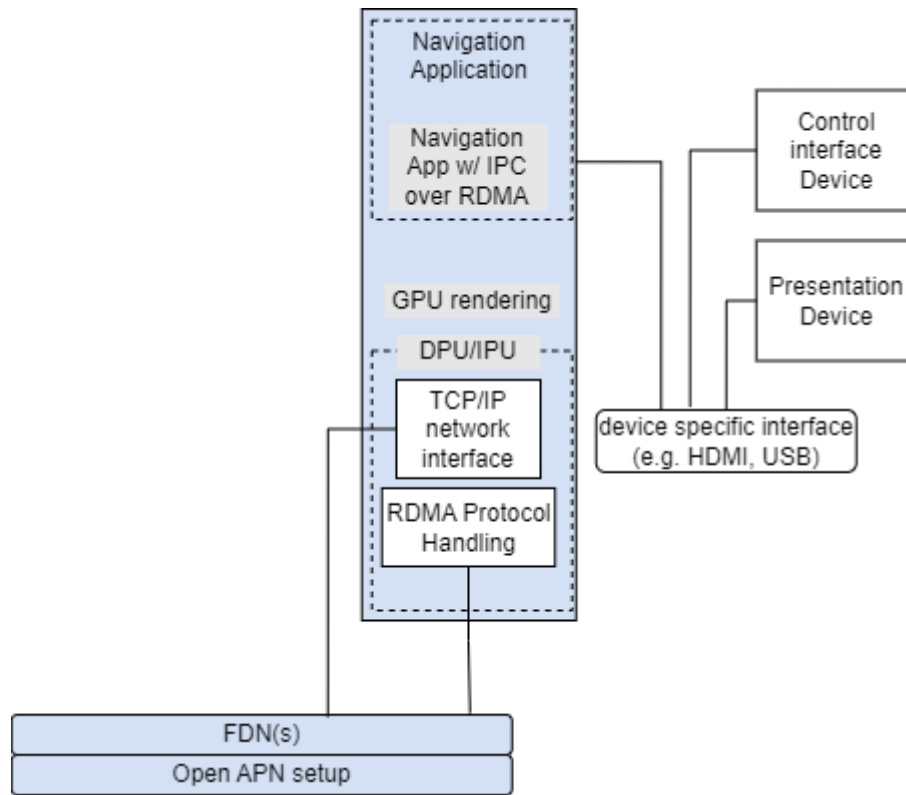
Figure 10. Initial RIM for Local Aggregation Node and Data hub / Streaming Hub

5.4. Expected Benefits

This section discusses the benefits of IOWN GF technology in RCRI UC. We show the qualitative benefits expected from this RIM compared to existing techniques for the possible bottleneck workload presented in section 3.2. The analysis will be conducted using feedback from the partial PoC, and a later revision of this document will be made for quantitative evaluation.

5.4.1. Communication for Remote Manipulating

Workload profile:

As described in section 3.2.1, the communication for control between the robot and the navigation application must meet the following KPIs.

- Manipulator control commands

    - Latency: 100 ms

    - Reliability: 99.999%

- Manipulator feedback, including haptics information

    - Latency: 10 ms

    - Reliability: 99.999%

Expected benefits:

Control communication to operate the robot and its onboard cameras and arms is relayed from the navigation application to the Mobile Robot via a local aggregation node. On long-distance fixed-line sections, a bandwidth-guaranteed deterministic network with Open APN is used. Therefore, the latency will be a fixed value (5 ms in this case) due to an optical transmission delay of 1,000 km, and packet loss will be a negligible probability.

For the wireless section, we need to wait for future PoC and experiments (such as packet loss rate measurements) to see how much reliability can actually be achieved by the system proposed in this RIM. With regard to latency, it is realistic in accordance with the 3GPP roadmap to achieve a latency of 5 ms. Protocol conversion between the wireless and fixed segments is expected to be reduced to less than 1 ms by using DCI architecture and DPU/IPU for higher-speed protocol decoupling.

5.4.2. Communication for Video Streams from Remote Robots

Workload profile:

As described in section 3.2.2, the communication for video streaming between the robot and the navigation application must meet the following KPIs.

- Video for operation

    - Spec: 8K/60 fps

    - Bandwidth: 72Gbps (uncompressed), 2.5G bps (JPEG XS)

    - Latency: 100 ms

    - Reliability: 99.999%

Expected benefits:

The video sent from the robot is sent to the local aggregation node via the radio I/F using low latency and low compression encoding such as JPEG XS. Using JPEG XS low latency encoding, 8K/60 video can be compressed to about 2.5 Gbps. From a bandwidth perspective, this is a realistic amount that can be transmitted by a single robot using next-generation wireless communications.

The node terminates the protocol at the radio level using DPU/IPU and then sends the video frame data to the Data Hub's pMEM using DMA mapping. Data Hub sends it to the Navigation Application using Open APN's RDMA protocol.

Data in the Application Node, which is also composed of DCI clusters, is copied into the GPU memory via DMA mapping from the DPU/IPU and sent directly to the Presentation Device through the rendering of the GPU process. In addition, the encoding of the video seen by the operator is encoded in low latency encoding such as JPEG XS, so unlike encoding such as HEVC (H.265), which involves frame-to-frame compression, no buffer is required, making it possible to prepare video for presentation with very low latency.

Although further research is needed on how to construct this process, the video rendering process delay in the processes in the node can be kept within xx ms, and the time from video reception by the DPU/IPU to video display by the Presentation Device can be reduced to less than xx ms.

The methods described in the previous section for increasing the reliability of the wireless section of a plant also have the same effect on improving the reliability of this workload profile. Therefore, it is believed that the required reliability can be ensured in combination with the guaranteed network reliability of long-distance communication by Open APN.

5.4.3. Aggregated Data flow via Data Hub

Workload profile:

As described in section 3.2.3, the communication for control between the robot and the navigation application must meet the following KPIs.

- Video and audio stream data

    o Raw bitrate: Up to 2.5G bps for multiple streams combined per robot using JPEG XS

    o Total uncompressed bitrate: 250G bps (100 robots)

Expected benefits:

The total low-compression video would be 250 Gbps, which would need to be relayed through a Data Hub/Streaming Hub and sent over a long-haul network to the Navigation Application. For long-distance transmission, the future transmission bandwidth contemplated by Open APN will be able to accommodate this. Regarding relaying within the Local aggregation node and Data Hub/Streaming Hub, CPU load and other issues related to data copy and transfer are considered to be a problem, but it is thought that this can be solved through technologies such as buffer-to-buffer transfer using RDMA with DCI. This issue needs to be demonstrated through PoC.

This RIM proposes a configuration in which video other than the operation screen, which is the focus of the operator's attention, is transmitted using high-compression encoding and sent to the Data Hub/Streaming Hub. The next-generation encoding, VVC (H.266), can compress 4K video to 25Mbps. Therefore, the total video capacity sent to the Data Hub/Streaming Hub is much smaller than that of low-compression video.

5.4.4. Security

The RIM will provide high data security for sensitive information through various measures such as zero-trust protection, strong encryption, and post-quantum protection. Data stored in the system will be encrypted with a suitable strength to prevent data leakage. Data transfer to remote locations will be done through quantum-resistant encryption, with limited access to authorized users. Communication between the data hub and the navigation application node will be protected by multi-factor security, providing better protection against external attacks. Data presented to the presentation device will only remain decrypted within the cluster and will not be stored on disk or access to external processes, ensuring the confidentiality of video and sensor data.

Overall, this RIM architecture enables the use of data across multiple locations beyond the boundaries of the local network while protecting data to criteria that exceed current industry standards.

6. Conclusion

In the RCRI, there are several technology gaps and issues that hinder the efficient remote operation of robots. These include unpredictable network constraints affecting capacity, latency, and reliability of communication, the trade-off between high reliability and low latency in end-to-end communication, lack of methods for streaming large volumes of high-definition video with low latency, instability of wireless coverage area, and operational limitation due to network boundary protection for security. To address these issues, the network and data hub service must provide high data security, stable network performance, secure communication channels between multiple sites, and technology that can guarantee wireless area coverage in a harsh environment.

The RIM described in this document uses the IOWN GF's architecture and technology to address these gaps. The RCRI requires a highly reliable and secure infrastructure for transferring large amounts of data with low latency. The IOWN technology defines a communication stack with low latency messaging using RDMA-based protocols for hardware offloading, hardware-based data transfer with adaptive video encoding, and guaranteed wireless coverage through multipath utilization and wireless link quality prediction. The RIM also implements zero-trust protection and strong cryptography for the secure storage and transfer of sensitive data. In addition, it will also require an infrastructure orchestrator for the overall IOWN architecture to integrate and combine these technologies to seamlessly manage geographically dispersed deployments and enable the secure transfer of large amounts of data.
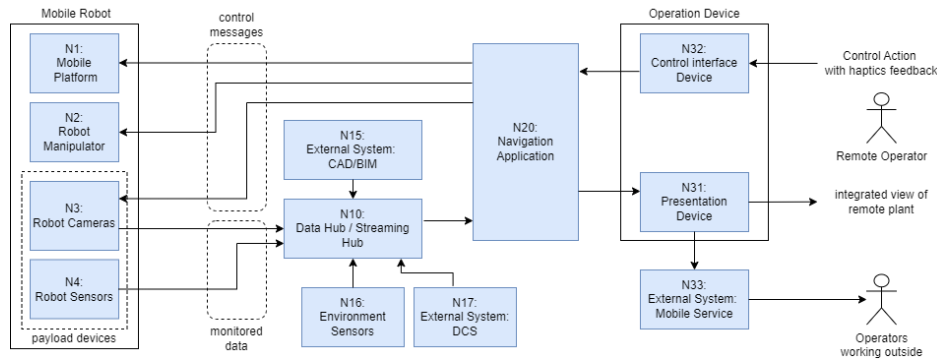
Appendix

A.1 Data Pipeline Diagram

Figure 11. Data Pipeline Diagram

A.2 Functional Node Profiles

ID	NAME	DESCRIPTION	ATTRIBUTES
n/a	Mobile Robot	Mobile robot with N1, N2, N3, and N4. Image: Robots should be remotely controlled with 100ms latency which allows seamless communication between robots and remote operators at a distance of 1,000 km. One remote operator will watch 20 video streams of UHD 60fps. Note: There are two types of communications: one for controlling the robot itself, manipulators, and sensors ("control messages"), and the other for output of inspection such as video stream or sensor data ("monitored data").	• #: 300 robots in a plant. o 100 robots working at the same time (5 robots per an inspector)

N1	Mobile platform	Articulated robots capable of moving through the plant as instructed by the N20 navigation application. They can carry multiple manipulators and sensors such as N2 Robot manipulators, N3 Robot cameras, and N4 Robot sensors. It receives control messages from N20 Navigation Application and sends responses to N20.	• #: 1 per a robot
N2	Robot manipulators	Manipulators attached to N1 Mobile platform that can do the following remote operations with haptic feedbacks as instructed by N20 navigation application. • Closing valves • Replacement of parts • Operation of electronic devices It receives control messages from N20 Navigation Application and sends responses to N20.	• #: 1 per a robot
N3	Robot cameras for inspection	Devices that capture steaming video and audio for remote inspection. Attached to a N1 mobile platform. N3 consist of multiple cameras and microphones and capture multiple video and audio streams using following devices. • High-definition camera (uncompressed 8 K 60 fps) • 3D (stereo or depth) camera • Infrared camera • X-ray camera • Gas monitoring camera • High precision microphone (96kHz x 24bit / channel) It receives control messages from N20 Navigation Application and sends responses to N20. It sends selected streams of video and audio data to N10 Streaming hub.	• #: Up to 5 cameras per a robot

N4	Robot sensors	Devices for sensing monitoring information on the inspected object and the surrounding environment. Attached to N1 Mobile platform. N4 consist of following sensors • LiDAR • Sensors (e.g., Temperature, humidity) • Tactile / hardness sensors • Gyro sensor for robot maneuvering • Location sensor (e.g., GPS) • Indoor positioning sensor It sends monitored data to N10 Data Hub.	• #: Up to 5 sensors per a robot
N10	Data Hub / Streaming Hub	A hub node to manage and store all the necessary data for remote inspection and relay it to the application. It receives one or multiple video and audio streams from N3 and multiple sensor data from N4 and relays them to N20 Navigation Application. Note: network and data hub service should provide high data security capable of protecting sensitive data at the industrial standard level.	• #: 1 per a plant site
N15	External System: CAD/BIM	An external system node that stores CAD/BIM data such as 3D maps of the plant and design information such as the location and geometry of equipment and corridors. It sends CAD/BIM data to N10 Data Hub.	• #: 1 per a plant site
N16	Environmental Sensors	Additional sensors attached to facilities such as the followings. • Temperature • Pressure • Oscillations • GAS It sends sensor data to N10 Data Hub.	• #: 20,000 per a plant site

N17	External System: DCS	An external system called DCS (distributed control system), which is a standard control system in a process plant in which sensors and autonomous controllers are installed in essential equipment throughout the plant. Note: Connecting the DCS to an external network requires particularly stringent security requirements	• #: 1 per a plant site
N20	Navigation Application	An application that integrates information from cameras, CAD/BIM data, sensors, etc., and renders real-time 3D video with audio and sensor data, as well as enabling remote robot navigation and remote control through instructions for areas requiring detailed investigation. The following functions are available as needed: • Synchronization • Rendering • Navigation It gathers monitored data from N10 Data Hub, integrates them, and sends integrated data to N31 Presentation device. It also receives control commands from N32 Control interface device and sends control messages to N1/N2/N3 and receives their response.	• #: 1 per a plant site
n/a	Operation device	User interface terminal with N31 and N32. Image: 	• #: 20 per a remote site
N31	Presentation device	HMD device with VR or AR glasses with speakers (optionally multiple large screens displays with speakers) that presents a video/audio stream of a remotely controlled field of view (target object). It receives integrated presentation data from N20 Navigation Application and shows it to a remote operator.	• #: 1 per an operation device

N32	Control interface device	User interface device for remote control of robots. It consists of a general user interface to navigate and control a remote robot. (e.g., HMD controller, gamepad, etc.) and haptics globes which receive haptics feedback from the plant site and presents it accurately with low latency. It receives user input from a remote operator and sends control commands to the N20 Navigation Application, with haptics feedback sent in the opposite direction.	• #: 1 per an operation device
N33	External System: Mobile Service	An external system that allows a supervisor outside of the remote site, such as at home, to be notified of the status of a remote inspection and to request assistance. It receives information on remote inspection application screens from N31 presentation devices.	• #: 1 per a plant site

A.3 Process and Dataflow Profiles of Each Functional Node

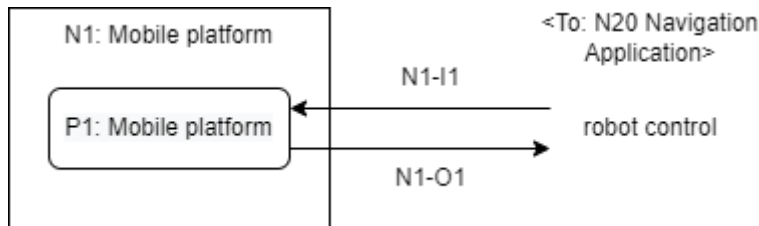## A.3.1 N1: Mobile platform
Description

Figure 12. N1: Mobile platform

The Mobile platform node (N1) is an articulated robot platform that is capable of moving through the plant as instructed by N20 navigation application. It is an appliance device that includes the following process.

- Mobile platform (P1)

Process Profiles

The following table shows the detailed description and major attributes of each process.

Table A-1.1 Process Profiles for N1: Mobile platform

ID	NAME	DESCRIPTION	ATTRIBUTES

| P1 | Mobile platform | • Receive control commands for remote control from Navigation application (N20)

• Move autonomously in the designated direction or to the indicated point

• Send the return value of the control command to Navigation application (N20) | • # of sources: one per a robot

• Possible tasks that can be offloaded to accelerators: none |

Dataflow Profiles

The following table shows the detailed description and the major attributes of the dataflows.

For reference, some remote operation APIs are standardized by ROS (Robot Operating System)http://wiki.ros.org/move_base#Action_API .

Table A-1.2 Dataflow Profiles for N1: Mobile platform

| ID	DESCRIPTION	ATTRIBUTES
N1-I1	• Control commands	• # of sources: one per a robot • Data size: 2KB / message • Occurrence rate: max to 60 messages / sec • 960 kbps at the maximum
N1-O1	• Feedback of control commands o move feedback (e.g., result, status, moved direction and distance)	• # of sources: one per a robot • Data size: 2KB • Occurrence rate: max to 60 messages / sec • 960 kbps at the maximum • Latency: 10 ms

A.3.2 N2 Robot manipulator
Description
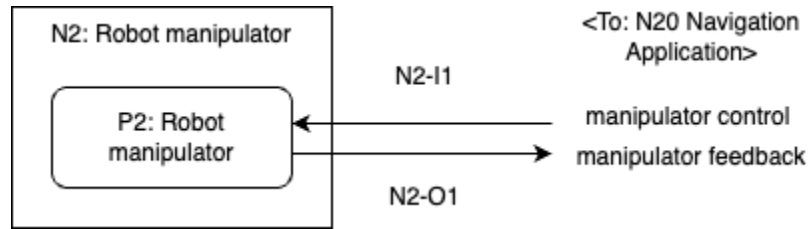
Figure 13. N2: Robot manipulatore

The Robot manipulator (N2) is an articulated robot platform that is attached to a Mobile platform (N1) and can manipulate the following operations with haptic feedback as instructed by N20 navigation application.

- Closing valves

- Replacement of parts

- Operation of electronic devices

It is an appliance device that includes the following process.

- Robot manipulator (P2)

Process Profiles

The following table shows the detailed description and major attributes of each process.

Table 1. Process Profiles for N2: Robot manipulator

ID	NAME	DESCRIPTION	ATTRIBUTES
P2	Robot manipulator	• Receive control commands for remote control from Navigation application (N20) • Move manipulator (e.g., robot hand) • Send the return value and feedback of the command to Navigation application (N20) o Haptics feedbacks, such as torque data of bolt screwing operation	• # of sources: one per a robot • Possible tasks that can be offloaded to accelerators: none

Dataflow Profiles

The following table shows the detailed description and the major attributes of the dataflows.

Table 2. Dataflow Profiles for N2: Robot manipulator

ID	DESCRIPTION	ATTRIBUTES

|		
N2-I1	• Manipulator control commands	• # of sources: one per a robot • Data size: 200 B / message • Occurrence rate: 500 messages / sec • Latency: 100 ms • 1 Mbps at the maximum • Reliability: 99.999%
N2-O1	• Manipulator feedbacks including haptics information	• # of sources: one per a robot • Data size: 48 B / message • Occurrence rate: 500 messages / sec (with compression) • 200 kbps at the maximum (per a robot) • Latency: 10 ms • Reliability: 99.999% • (Ref. "*Teleoperation*" use case analysis from IEEE 1918.1 "Tactile Internet")

A.3.3 N3 Robot camera
Description
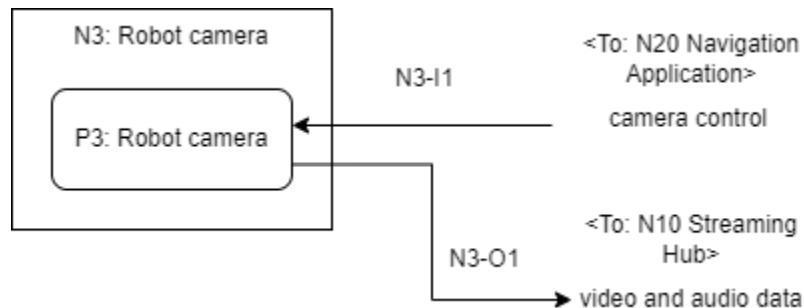
Figure 14. N3: Robot camera

The Robot camera (N2) is a set of cameras attached to a Mobile platform (N1) and can capture and send to Data hub / Streaming hub (N10) a variety of video and audio needed to operate the robot and enable it to observe its surroundings. Some cameras can change their direction, zoom, etc., by instructions from Navigation application (N20).

- It is necessary to find out the cracking area that the size is 0.1 mm to be inspected. For this solution level, 16K is not necessary if we approach a defect area with a robot arm or enlarge the image with an optical lens.

- A stereo camera will be better for setting up a robot arm to the object than mono

- Video data should be supplied with the 3D data to identify areas in need of repair

It includes the following process:

- Robot camera (P3)

Process Profiles

The following table shows the detailed description and major attributes of each process.

Table 3. Process Profiles for N3: Robot Camera

ID	NAME	DESCRIPTION	ATTRIBUTES
P3	Robot camera	- Receive control commands for remote control from the Navigation application (N20) - Changes the direction, zoom, filters, and other shooting parameters based on remote instructions from N20. - Capture video and audio streams - Send multiple streams of video and audio data to the Streaming hub (N10)	- # of sources: one per a robot - Possible tasks that can be offloaded to accelerators: none

Dataflow Profiles

The following table shows the detailed description and the major attributes of the dataflows.

Table 4. Dataflow Profiles for N3: Robot Camera

ID	DESCRIPTION	ATTRIBUTES
N3-I1	- Control command, which can change direction of a camera.	- # of sources: one per a robot - Data size: 2KB / message - Occurrence rate: max to 10 messages / sec - 96 kbps at the maximum

N3-O1	• Selected streams of video and audio data
	
	    ○ High-definition camera: uncompressed 8 K 60 fps (about 48 ～ 72 Gbps without compression)
	
	    ○ 3D (stereo or depth) camera: 4K
	
	    ○ Manipulator close-up camera: 4K
	
	    ○ Infrared camera: 4K
	
	    ○ X-ray camera: 4K
	
	    ○ High precision microphone: 96kHz x 24bit x 2 channel (4.6 Mbps)
		• # of sources: Up to 5 cameras and 1 microphone per a robot
		
		• Data size: see the left column for each stream
		
		• Bitrate: Up to 2.5 Gbps for multiple streams combined assuming JPEG XS compression.
		
		• Latency: 100 ms
		
		• Reliability:
		
		    ○ Video for operation: 99.999% (As frame drop rate. However, it is desirable to guarantee a maximum video interruption time, which is targeted at 0.1 second.)
		
		    ○ Video for inspection: 99.9%

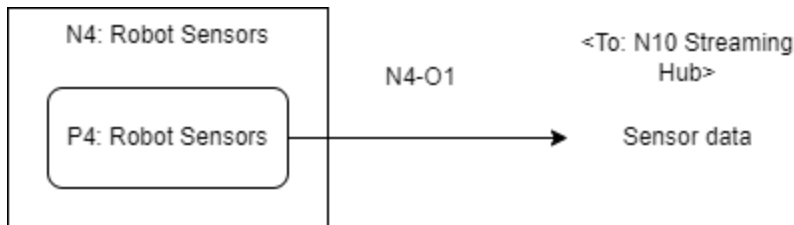## A.3.4 N4 Robot sensors

Description

Figure A-1.5 N4 Robot sensors

The Robot sensors (N4) are a group of sensors attached to the mobile platform (N1) that can report various sensing data observed around the robot to the streaming hub (N10).

It includes the following process:

• Robot Sensors (P4)

Process Profiles

The following table shows the detailed description and major attributes of each process.

Table 5. Process Profiles for N4: Robot sensors

ID	NAME	DESCRIPTION	ATTRIBUTES

	Robot sensors	• Send sensed data to Data Hub (N10)	• # of sources: one per a robot • Occurrence rate: 60 times per sec (60Hz)
P4			

Dataflow Profiles

The following table shows the detailed description and the major attributes of the dataflows.

Table 6. Dataflow Profiles for N4: Robot sensors

ID	DESCRIPTION	ATTRIBUTES

N4-O1	• LiDAR (for precise robot navigation)
	    o Data rate: 32~64 Mbps / source (not compressed)
	• Temperature sensor
	• Gas concentration sensor (interlocking to stop the robot in dangerous areas)
	• Humidity
	• Tactile Sensors
	• Gyro sensor
	    o Data rate: 144 kbps / source (3 axis x 24bit x 2 KHz)
		• # of sources: one per a robot (each sensor has one instance per a robot)
		• Data size: see the left column for each stream
		• Occurrence rate: see the left column for each stream
		• Bitrate: Up to 100 Mbps for multiple sensors combined

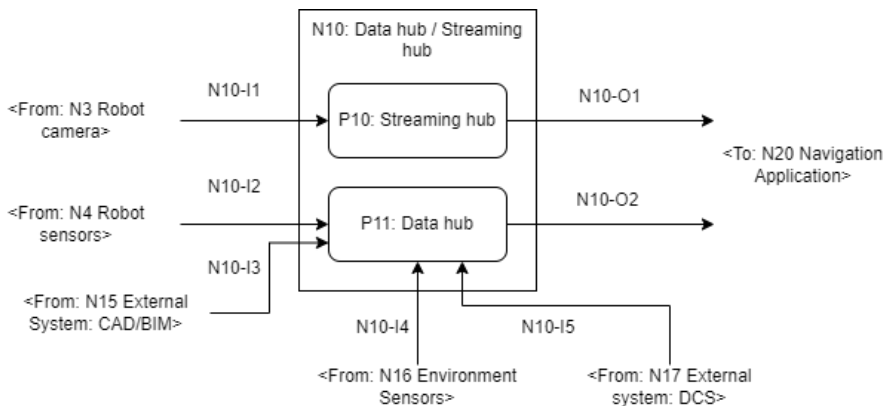# A.3.5 N10 Data hub / Streaming hub
Description

Figure A-1.6 N10: Streaming hub / Data hub

The Streaming hub / Data hub (N10) is the hub node for aggregating data and passing it to the application. It is impossible for plant owners to store the data outside of the site without strong security systems.

It includes the following process:

- Streaming hub (P10)

- Data hub (P11)

Process Profiles

The following table shows the detailed description and major attributes of each process.

Table 7. Process Profiles for N10: Streaming hub / Data hub

ID	NAME	DESCRIPTION	ATTRIBUTES
P10	Streaming hub	• Receive video and audio stream data from Robot cameras (N3) • Store stream data for later analysis • (Select and switch stream data?) • Send video and audio stream data to Navigation application (N20)	• # of sources: one per a node
P11	Data hub	• Receive sensor data from Robot sensors (N4) • Retrieve 3D map of the plant and information on the layout of facilities, etc. from CAD/BIM Data Store (N15) • Receive sensor data from Environment Sensors / DCS (N16) • Store sensor data for later analysis • Send integrated data based on queries such as location to Navigation application (N20)	# of sources: one per a node

Dataflow Profiles

The following table shows the detailed description and the major attributes of the dataflows.

Table 8. Dataflow Profiles for N10: Streaming hub / Data hub

ID	DESCRIPTION	ATTRIBUTES

N10-I1	• Video and audio stream data	• # of sources: 100 • Bitrate: Up to 2.5 Gbps for multiple streams combined per a robot • Total Bitrate: 250 Gbps
N10-I2	• Sensor data from robots	• # of sources: 100 • Bitrate: Up to 100 Mbps for multiple sensors combined • Total Bit rate: 10 Gbps
N10-I3	• 3D map of the plant including the layout of facilities, location of environmental sensors, etc.	• Data size: 200 MB
N10-I4	• Sensor data from environmental sensors	• Bit rate: 400 MB / sec
N10-I5	• Sensor data from DCS • Monitoring status of facilities	• Bit rate: 400 MB / sec
N10-O1	• Video and audio stream data	• # of sources: up to 20 (remote operators) • Bitrate: Up to 50 Gbps
N10-O2	• Selected data based on queries	• # of sources: up to 20 (remote inspectors) • Bitrate: Up to 2 Gbps

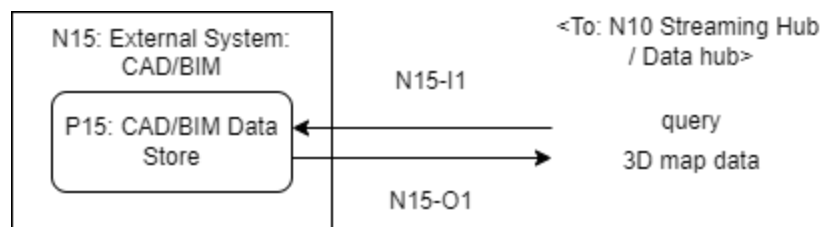## A.3.6 N15 External System: CAD/BIM
Description

Figure 15. N15 External System: CAD/BIM

The CAD/BIM Data Store (N15) is a database or system that stores the engineering design information of the plant. It provides a 3D map of the plant and information on the layout of facilities, etc., to a Streaming hub / Data hub (N10). In

this DPD, N15 is modeled as a virtual data store, but in the actual system, it is assumed to be part of the system used in existing plant operations.

It includes the following process:

- CAD/BIM Data Store (P15)

Process Profiles

The following table shows the detailed description and major attributes of each process.

Table 9. Process Profiles for P15: CAD/BIM Data Store

ID	NAME	DESCRIPTION	ATTRIBUTES
P15	CAD/BIM Data Store	- Receive queries from Streaming hub / Data Hub (N10) - Send 3D map of the plant and information on the layout of facilities, etc. to Streaming hub / Data Hub (N10) o Coded BIM data is useful for accurate location when aerial photography by drone in 3D.	- # of sources: one per a plant

Dataflow Profiles

The following table shows the detailed description and the major attributes of the dataflows.

Table 10. Dataflow Profiles for P15: CAD/BIM Data Store

ID	DESCRIPTION	ATTRIBUTES
N15-I1	- Query to select the required map data	- # of sources: one per a plant - Occurrence rate: one query per a day
N15-O1	- 3D map of the plant including the layout of facilities, location of environmental sensors, etc.	- Data size: 200 MB per a plant

A.3.7 N16 Environment Sensors
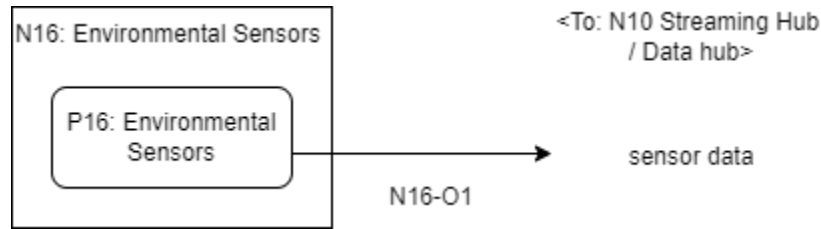**Description**

Figure 16. N16 Environment Sensors

The Environment Sensors (N16) is modeled as a virtual sensor data source that provides various sensor data and monitors the status of plant facilities.

It includes the following process:

- Environment Sensors (P16)

Process Profiles

The following table shows the detailed description and major attributes of each process.

Table 11. Process Profiles for P16 Environment Sensors

ID	NAME	DESCRIPTION	ATTRIBUTES
P16	Environment Sensors	• Send sensor data to Streaming hub / Data Hub (N10)	• # of sources: 20,000 per a plant • Occurrence rate: 5 KHz

Dataflow Profiles

The following table shows the detailed description and the major attributes of the dataflows.

Table 12. Dataflow Profiles for P16 Environment Sensors

ID	DESCRIPTION	ATTRIBUTES
N16-O1	• Sensor data from environmental sensors • Monitoring status of facilities	• # of sources: 20,000 • Occurrence rate: 5 KHz • Bit rate: 20,000 byte / sec per a source • Total bit rate: 400 MB / sec

A.3.8 N17 External System: DCS
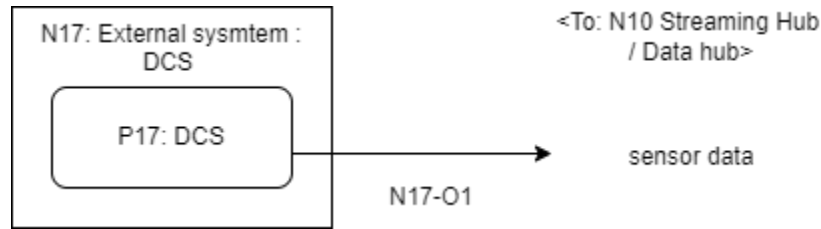**Description**

Figure 17. N17 External System: DCS

The external system: DCS (N17) is modeled as a virtual sensor data source that provides various sensor data and monitoring status of plant facilities, provided via DCS (distributed control system), an existing system for plant control.

Basically, DCS data in chemical plants must be kept out of the gate, and to prevent hijacking or rewriting by outside parties, DCS data must be kept especially highly confidential.

It includes the following process:

- DCS (P17)

Process Profiles

The following table shows the detailed description and major attributes of each process.

Table 13. Process Profiles for P17 DCS

ID	NAME	DESCRIPTION	ATTRIBUTES
P17	DCS	• Send sensor data to Streaming hub / Data Hub (N10)	• # of sources: one per a plant • Occurrence rate: 5 KHz

Dataflow Profiles

The following table shows the detailed description and the major attributes of the dataflows.

Table 14. Dataflow Profiles for P17 DCS

ID	DESCRIPTION	ATTRIBUTES

N17-O1	• Monitoring status of equipment
	
	• Sensor data from DCS
	
	    ○ Temperature
	
	    ○ Pressure
	
	    ○ Oscillations
	
	    ○ GAS
	
	Note: The same type of sensor data is collected in duplicate from N16 and N17. This is because some sensors are accommodated in the DCS as existing systems, while retrofitted environmental sensors may send data directly.
		• # of sources: 20,000
		
		• Occurrence rate: 5 KHz
		
		• Bit rate: 20,000 byte / sec per a source
		
		• Total bit rate: 400 MB / sec

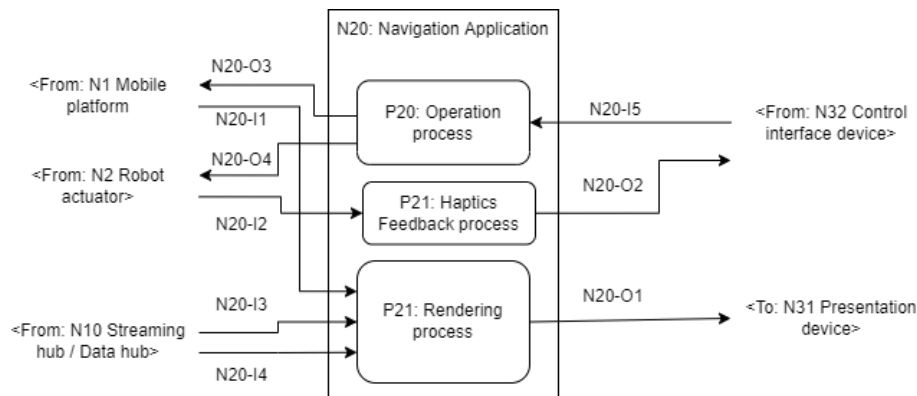## A.3.9 N20 Navigation Application
Description

Figure 18. N20: Navigation Application

Navigation Application (N20) is a central application node for remotely controlling robots to monitor and operate equipment in a plant.

- The application mainly operates remote robots at speeds of 10 km/h or less, which is faster than Level 4 for automobiles.

- L5 is required for cooperation with other robots and cooperative behavior. (Currently, L5 has a delay of 70 msec, so if it moves too fast, it will collide with people. 5 km/h is safe because it requires less energy).

- A 4D map is created, including information from sensors. Automated creation of the map reduces the burden on workers.

It includes the following processes:

- Operation process (P20)

- Rendering process (P21)

Process Profiles

The following table shows the detailed description and major attributes of each process.

Table 15. Process Profiles for N20: Navigation Application

ID	NAME	DESCRIPTION	ATTRIBUTES

P20	Operation process	• Receive remote control instructions from remote operator via Control interface device (N3). Instructions include such kinds of operations.
		
		    o move to next location
		
		    o change view or other parameters of robot cameras
		
		    o move manipulators
		
		    o etc.
		
		• Interpret remote control instructions and translate them into device-specific commands.
		
		• Send to Mobile platform (N1) and Robot manipulators (N2).
			• # of sources: one per a remote plant

P21	Haptics Feedback process	• Receive haptics feedback from robot manipulators • Send feedbacks to control interface device (N32)	• # of sources: one per a remote plant

P22	Rendering process	• Receive audio and video streams form Streaming hub / Data hub (N20)
		
		• Send query to N20 and receive multiple kinds of sensor data and 3D map data
		
		• Render integrated real-time 3D video and audio streams integrated with sensor data. It needs following functionalities.
		
		    o Synchronization
		
		    o Rendering
		
		    o Navigation
		
		• Send integrated operating screen information to the Presentation device (N31).
			• # of sources: one per a remote plant

Dataflow Profiles

The following table shows the detailed description and the major attributes of the dataflows.

Table 16. Dataflow Profiles for N20: Navigation Application

ID	DESCRIPTION	ATTRIBUTES
N20-I1	• Feedback of control commands o move feedback (e.g., result, status, moved direction and distance)	• # of sources: one per a robot • Data size: 2KB • Occurrence rate: max to 60 messages / sec • 960 kbps at the maximum • Latency: 10 ms
N20-I2	• Manipulator feedbacks including haptics information	• # of sources: one per a robot • 200 kbps at the maximum (per a robot) • Latency: 10 ms
N20-I3	• Selected video and audio stream data from robots	• # of sources: up to 20 (remote inspectors) • Bitrate: Up to 1,440 Gbps
N20-I4	• Selected sensor data from robots	• # of sources: up to 20 • Bitrate: Up to 2,000 Mbps
N20-I5	• User input commands for Robot movement and manipulator control	• # of sources: up to 20 • Bitrate: 1 Mbps per a source
N20-O1	• Rendered operating screen images and integrated information	• # of sources: up to 20 • 4K / 60 FPS
N20-O2	• Manipulator feedbacks including haptics information	• # of sources: one per a robot • 200 kbps at the maximum (per a robot) • Latency: 10 ms

N20-O3	• Control commands for robot movements	• # of sources: up to 100 • Bitrate: 960 kbps per a robot
N20-O4	• Control commands for manipulator	• # of sources: up to 20 • Bitrate: 1 Mbps per a robot • Latency: 100 ms

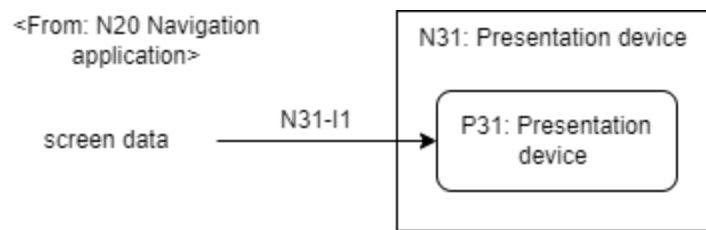## A.3.10 N31 Presentation device
Description

Figure 19. N31 Presentation device

Presentation device (N31) is a user interface device with an HMD device with VR or AR glasses, speakers, and headset that presents a video/audio stream of a remotely controlled field of view (target object).

It includes the following process:

- Presentation device (P31)

Process Profiles

The following table shows the detailed description and major attributes of each process.

Table 17. Process Profiles for N31 Presentation device

ID	NAME	DESCRIPTION	ATTRIBUTES
P31	Presentation device	• AR monitor ○ It shows precautions by the operation standard. (e.g., dangerous work such as opening and closing pressure valves) • XR Monitor	• # of sources: 20 (remote inspectors) • Occurrence rate: 60 FPS rendering

Dataflow Profiles

The following table shows the detailed description and the major attributes of the dataflows.

Table 18. Dataflow Profiles for N31 Presentation device

ID	DESCRIPTION	ATTRIBUTES
N31-I1	• Rendered operating screen images and integrated information	• # of sources: up to 20 • 4K / 60 FPS

A.3.11 N32 Control Interface device
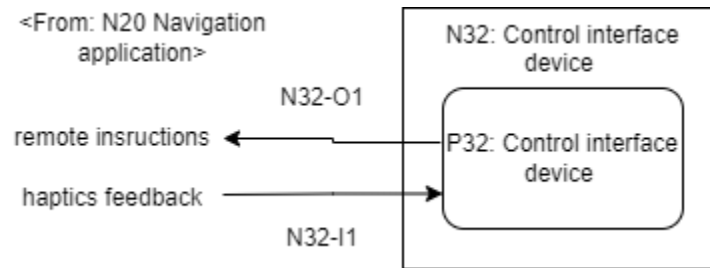**Description**

Figure 20. N32 Control Interface device

Control Interface device (N32) is a user interface device for the remote control of robots. It has a general user interface to navigate and control a remote robot. (e.g., HMD controller, gamepad, etc.) and haptics globes that receive haptics feedback from the plant site and present accurately with low latency.

It includes the following process:

• Control Interface device (P32)

Process Profiles

The following table shows the detailed description and major attributes of each process.

Table 19. Process Profiles for N32 Control Interface device

ID	NAME	DESCRIPTION	ATTRIBUTES
P32	Control Interface device	• Haptics Glove Pressure Feedback • Game machine controller that we are familiar with using	• # of sources: 20 (remote inspectors)

Dataflow Profiles

The following table shows the detailed description and the major attributes of the dataflows.

Table 20. Dataflow Profiles for N32 Control Interface device

ID	DESCRIPTION	ATTRIBUTES
N32-I1	• Manipulator feedbacks including haptics information	• # of sources: 20 • 200 kbps per a source • Latency: 10 ms

N32-O1	• User input commands
	    o for Robot movements (960 Kbps)
	    o for manipulator control (1 Mbps)
		• # of sources: up to 20
		• Bitrate: around 1 Mbps combined per a source

Acknowledgments

History

REVISION	RELEASE DATE	SUMMARY OF CHANGES
1.0	April 26, 2023	Initial Release

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