Metaverse Standards Forum
Remote Assistance for Autonomous Robots

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Use Case Title
Remote Assistance for Autonomous Robots

Use Case Identifier

MSF2025-RAR-001

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Summary of Use Case

Description: A standardized, interoperable approach is required to enable real-time remote assistance for autonomous robots in industrial production environments through synchronized digital twins and extended reality (XR) interfaces. When robots encounter anomalous equipment states that halt production, the system autonomously requests human operator support, who can then diagnose and resolve issues through immersive interfaces that provide live video feeds, synchronized digital twin representations, and remote control capabilities. This framework minimizes production downtime, reduces the need for on-site technical expertise, and enables small operation teams to handle multiple simultaneous equipment failures across distributed manufacturing facilities.

Benefits:

- **Reduced Production Downtime:** Enables immediate response to equipment failures through autonomous alerting and remote diagnostics “minimizing line stoppages and associated costs.”
- **Reduced Mean Time to Repair (MTTR):** XR and digital twin technologies improve maintenance efficiency by accelerating diagnostics and reducing costs. Siemens pilots report major savings, and IEEE studies confirm faster, more accurate fault detection. While results vary, evidence shows these tools consistently shorten MTTR compared to traditional methods.
- **Optimized Personnel Utilization:** Allows a single operator to support multiple robots across different locations simultaneously, addressing personnel shortages and reducing required on-site staff.
- **Enhanced Problem-Solving Capabilities:** Provides operators with comprehensive situational awareness through synchronized digital twins, live video feeds, and contextual production data for faster, more accurate diagnostics.
- **Knowledge Preservation & Transfer:** Captures troubleshooting procedures and solution data to build institutional knowledge and training resources for recurrent issues.
- **Predictive Maintenance Enablement:** Collects performance and maintenance data to identify patterns, forecast potential failures, and enable proactive maintenance scheduling.

- **Cross-Platform Operational Consistency:** Ensures identical diagnostic and control capabilities across different XR devices and display systems, from basic screens to immersive VR headsets.
- **Sustainable Resources:** Promotes enterprise reuse via modular AAS-compliant twin libraries, supported by open-source ecosystems (e.g., Eclipse BaSyx), ensuring scalable updates without vendor lock-in.

Contributors and Supporters

- Industrial Metaverse Working Group
- MSF Domains (Peer Review)
- Use Case Taskforce

Keywords

XR Devices, Industrial Production, Maintenance, Digital Twin, Autonomous Systems, Predictive Maintenance, Remote Diagnostics, Human-Robot Collaboration, Real-Time Synchronization, Industrial Metaverse

Actors/Entities

- **Manufacturer:** Automotive and industrial producers who operate production facilities and drive metaverse integration to achieve business benefits including reduced downtime and optimized personnel costs.
- **Operators:** Technical specialists responsible for monitoring, diagnosing, and resolving robot issues through remote interfaces, possessing expertise in both robotics and the specific production processes.
- **Robots (Assets):** Autonomous production equipment capable of self-diagnosis, autonomous support requests, and remote control through digital twin synchronization.
- **Digital Twins:** Virtual representations of physical robots that mirror real-time behavior, characteristics, and performance using sensor data, simulation, and modeling techniques.
- **Standards Development Organizations (SDOs):** IEEE, IEC, ISO and similar bodies that define interoperability standards for metaverse applications in industrial contexts.
- **Machine Builders (OEMs):** Robot manufacturers who implement SDO standards, design metaverse-compatible systems, and provide integration specifications and user documentation.
- **XR Software Providers:** Developers who create metaverse experiences and digital twin platforms aligned with manufacturer requirements and OEM design principles.
- **XR Hardware Developers:** Manufacturers of specialized XR devices, glasses, and accessories optimized for industrial remote assistance applications.
- **Assurance Providers:** Certification authorities and auditors who verify compliance with metaverse standards and security requirements.

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Detailed Description of Use Case/Scenario

Preconditions:

1. **Technical Infrastructure:** Robots are equipped with comprehensive sensor arrays, diagnostic systems, and standardized communication interfaces supporting real-time data streaming and remote intervention. Manufacturing facilities operate centralized monitoring platforms that integrate predictive maintenance algorithms, knowledge-based troubleshooting guidance, multi-user XR collaboration environments, and real-time digital twin synchronization.
2. **Operational Readiness:** Personnel receiving extensive training on XR interfaces, diagnostic procedures, and specific robotic systems. Clear escalation protocols established for complex scenarios requiring specialized expertise. Security and access controls implemented for remote operation privileges.
3. **System Integration:** Digital twin synchronization protocols established between physical robots and virtual representations. Real-time communication infrastructure supporting sub-100ms latency requirements. Cross-platform interoperability standards implemented across all XR devices and control systems.
4. **Data Standardization:** Standard compliant data interfaces (e.g., MTConnect Version 2.5-compliant, February 2025 SysML enhancements) providing standardized equipment communication across all robotic assets. Unified semantic models for equipment status, error conditions, and performance metrics established across all manufacturing systems.

Main Flow:

- **Scenario 1:** Multi-Robot Crisis Management in Automotive Assembly

1. Three welding robots simultaneously detect anomalous equipment states on automotive assembly line in Detroit, Michigan
2. Robots autonomously transmit detailed support requests with error codes and sensor data via adopted interfaces (e.g., MTConnect-compliant)
3. Centralized monitoring system prioritizes alerts based on production impact and resource availability
4. Operator Sarah in the central control room accesses live video feeds and examines synchronized digital twin showing real-time positioning
5. Using gesture controls on her AR headset, Sarah tests solutions and executes corrections on the physical robots
6. All three robots resume normal operation with minimal production disruption

- **Scenario 2:** Predictive Maintenance Activation in Packaging Operations

1. Packaging robot's monitoring system at Houston facility detects abnormal vibration patterns indicating bearing failure
2. Predictive algorithms forecast 48-hour failure window with 95% confidence
3. System autonomously schedules maintenance during next production break
4. Supervisor Bernard remotely validates diagnosis from the Berlin engineering center and prepares maintenance procedure through tablet interface
5. AR overlays guide on-site technician Hana through bearing replacement with torque specifications
6. Robot returns to service with zero unplanned downtime

- **Scenario 3:** Remote Expert Collaboration for Complex Repairs

1. Specialized assembly robot at Phoenix manufacturing facility experiences mechanical failure beyond local expertise
2. System automatically connects to global expert network matching failure pattern
3. Specialist Dr. Yuki joins session from Osaka using WebXR interface on standard browser
4. Shared digital twin manipulation enables guided repair procedure with real-time annotation
5. Spatialized audio communication with automatic transcription provides real-time instruction and feedback
6. Complex repair completed without requiring expert physical presence

- **Scenario 4:** Assembly Line Quality Control Audit

1. Quality auditors conduct routine inspection of robotic welding stations across Stuttgart and Vienna facilities
2. Tablet interfaces provide access to digital twins with performance metrics
3. System flags two robots showing deviations from quality standards
4. Lead auditor Kamila (remote from Atlanta quality center) and local auditor Carlos (Stuttgart) annotate digital twins with specific concerns and recommendations
5. Maintenance scheduling system automatically routes adjustment requirements with priority levels
6. Quality standards maintained across all production lines through continuous monitoring

- **Scenario 5:** Cross-Facility Robot Training and Procedure Updates

1. Manufacturing conglomerate rolls out new assembly procedures across global facilities (London, Bern and Kraków)
2. Training coordinator Joe demonstrates updated workflows simultaneously to all locations via XR platform
3. Local teams practice new procedures on digital twins of specific robot models
4. System tracks performance metrics and proficiency levels in real-time with adaptive difficulty scaling
5. Certification records automatically generated for operators demonstrating mastery
6. Consistent procedure implementation achieved across all manufacturing sites within 48 hours

Alternative Flow

- **Scenario 1 Alternatives:** Multi-Robot Crisis Management

1. **Network Performance Degradation**
   - Operator Sarah attempts fine-grained welding path correction when network latency increases from baseline 25ms to 120ms during critical manipulation:
     - System automatically switches to predictive display mode showing anticipated robot movements based on last known trajectory
     - Sarah receives notification: "Adaptive latency compensation active - control precision maintained with 95ms prediction buffer"
     - Critical safety functions remain operational with local processing at robot controller level, preventing unsafe operations
     - Control effectiveness maintained through hybrid local-remote control architecture with graceful degradation, allowing Sarah to complete the corrective action successfully
2. **Sensor Data Incompleteness**

- Operator Sarah faces diagnostic challenge when one robot's primary position encoders fail during the multi-robot assembly line crisis:
  - Digital twin highlights missing data streams and activates simulation mode based on last known kinematic parameters and motor current inference
  - System suggests alternative diagnostic approaches using available camera feeds and operational history from the other two functioning robots
  - Sarah can request manual inspection of specific components by on-site personnel, with AR-guided verification points displayed on her headset
  - Diagnostic confidence levels displayed throughout the process (Current: 73% based on indirect sensing), enabling Sarah to make informed decisions about proceeding with repairs

3. Multi-Operator Control Conflict

- Operator Sarah and senior operator Michael both attempt to control the same critical welding robot simultaneously during the three-robot crisis:
  - System implements conflict resolution protocols using a defined authorization hierarchy that grants control to higher-priority production-critical tasks
  - Both Sarah and Michael see each other's cursors, annotations, and intended control inputs in the shared digital twin environment
  - Control permissions automatically transfer based on task progression, with explicit handoff confirmation protocols
  - Collaboration mode enables parallel diagnostic work with Sarah analyzing root cause on Robot 1 while Michael prepares corrective actions for Robot 2, maximizing crisis response efficiency

- **Scenario 2 Alternatives:** Predictive Maintenance Activation

1. False Positive Identification

- Supervisor Bernard reviews vibration alert from Houston facility that conflicts with recent bearing replacement records (replaced 3 weeks prior):
  - System provides confidence scoring (Current alert: 78% confidence) and historical accuracy metrics (This model: 89% positive predictive value over 2,400 alerts)
  - Bernard overrides maintenance recommendation with explanatory notes: "Recent bearing replacement verified, likely false positive due to break-in period vibration signature"
  - Machine learning model receives negative feedback from Bernard's expert assessment to refine future bearing break-in pattern recognition
  - Alert threshold adjusted for recently serviced components with automatic reset after 500 operating hours, improving system accuracy

2. Part Supply Chain Disruption

- Supervisor Bernard discovers the critical bearing for Houston facility has 6-week lead time during scheduled maintenance window:
  - System suggests temporary mitigation procedures based on Bernard's input: reduced speed operation (75% rated capacity), increased monitoring frequency (hourly vs. daily checks)

  - Alternative suppliers automatically researched across approved vendor list with cross-reference to Original Equipment Manufacturer (OEM) compatibility specifications
  - Expedited shipping options presented with cost-benefit analysis: Air freight vs. production loss risk
  - Bernard adjusts maintenance schedule to prioritize continuous monitoring of at-risk component with automated escalation if condition deteriorates, coordinating with on-site technician Hana for enhanced visual inspections
- **Scenario 3 Alternatives:** Remote Expert Collaboration

1. **Expert Availability Constraints**
   - Phoenix facility's local operator contacts system for specialized support on the complex servo motor controller failure, but Dr. Yuki and other specialists are unavailable in current time zone (10:30 am local Arizona time, early morning in Japan):
     - System escalates to next-tier support: Senior technician from Chicago (04:30 pm local time) with broader industrial robotics expertise though less model-specific experience
     - Knowledge base provides annotated solutions from 14 similar historical cases (8 resolved remotely, 6 required on-site intervention)
     - AI-assisted diagnostic system provides decision tree with confidence scoring at each branch point
     - Manufacturer's engineering team (Germany) automatically notified for high-severity issues; Dr. Yuki receives escalation notice for morning follow-up with projected 4-hour response time during Japanese business hours
2. **Multilingual Technical Collaboration**
   - Dr. Yuki (Osaka, native Japanese) collaborates with Phoenix facility's local operator (native English) on complex hydraulic system failure requiring precise technical communication:
     - System provides real-time technical terminology standardization using manufacturing-specific glossaries (e.g., ISO 8373 robotics vocabulary, IEC 60050 electrical terminology)
     - Visual annotation tools highlight specific components using standardized part numbering systems and universal nomenclature in Dr. Yuki's WebXR interface
     - Procedure demonstrations use animated sequences with symbolic notation per ISO 3864-3 to ensure clarity beyond verbal communication
     - Technical measurement units automatically displayed in both operator's preferred formats (metric/imperial) with conversion verification
     - Automatic transcription in both Japanese and English creates searchable maintenance record with terminology cross-reference for future use by Phoenix facility team

- **Scenario 4 Alternatives:** Quality Control Audit

1. **Quality Standard Interpretation Alignment**
   - Quality auditors Kamila (Atlanta) and Carlos (Stuttgart) identify need to clarify weld penetration depth measurement methodology during their routine inspection

(specification states "3.5mm ±0.3mm" but measurement technique requires standardization):
  - System provides reference implementations from corporate quality manual with measurement protocol video demonstrations
  - Kamila and Carlos collaboratively review measurement technique in shared VR environment using calibrated digital calipers on reference specimens
  - Historical measurement data analyzed across 2,847 similar audits to identify consistency patterns and process variation sources
  - Refined measurement protocol issued with clarified methodology and published to all facilities within 24 hours, ensuring global consistency between Stuttgart, Vienna, and all other facilities

2. **Measurement Calibration Discrepancies**
   - Lead auditor Kamila discovers laser measurement tools showing 0.2mm systematic variance between identical robot stations in Stuttgart (Robot A: 3.48mm average, Robot B: 3.68mm average on same test piece):
     - System triggers automatic calibration routine against known NIST-traceable reference standards (gauge blocks)
     - All measurements from affected station in past 72 hours flagged for potential review (184 measurements across 6 production runs)
     - Alternative measurement methodologies deployed: coordinate measuring machine (CMM) verification on sample parts confirms Robot B measurements are accurate; Robot A sensor requires recalibration
     - Carlos conducts on-site verification while Kamila monitors remotely; root cause analysis identifies environmental temperature differential (4.2°C) affecting laser sensor accuracy; thermal compensation algorithm updated across Stuttgart and Vienna facilities

- **Scenario 5 Alternatives:** Cross-Facility Training

1. **Procedure Compatibility Issues**
   - Training coordinator Joe discovers new assembly workflow requires sensor capabilities not available in older generation Fanuc robots at Kraków facility (2017-era controllers lack required digital I/O channels):
     - System identifies compatibility constraints during Joe's training preparation phase through automated robot capability assessment against procedure requirements
     - Alternative procedures generated automatically for legacy equipment: 3-step manual verification sequence replaces single automated sensor check
     - Manufacturing engineers receive specific modification requirements with cost-benefit analysis: retrofit cost vs. workaround productivity impact
     - Joe splits training into two tracks delivered simultaneously via XR platform: Standard procedure for modern equipment (London and Bern facilities) and adapted procedure for legacy systems (Kraków facility) with planned equipment upgrade scheduled

2. **Operator Skill Development**

- During Joe's training session, a new operator at the London facility struggles with complex 3D spatial gesture controls during advanced procedure training (proficiency score: 54% vs. required 80% for certification):
  - System automatically detects performance patterns indicating spatial manipulation difficulties through motion tracking analysis and hand-eye coordination metrics
  - Joe reviews the adaptive training recommendations and authorizes personalized modules with progressive complexity:
    - 2D tablet interface alternative introduced for preliminary concept learning
    - Haptic feedback intensity increased by 40% to improve proprioceptive awareness
    - Gesture vocabulary reduced from 15 to 8 essential commands initially, with gradual expansion
  - Training pace automatically adjusted with mastery-based progression: operator must achieve 85% proficiency on simplified interface before advancing to full complexity
  - Joe schedules one-on-one mentoring session with experienced operator from Bern facility who successfully completed similar skill development path 6 months prior
  - Performance tracking shows 23% improvement after 4 hours of adaptive training; Joe extends projected certification timeline from 3 days to 5 days with 92% predicted success rate, ensuring quality over speed

Postconditions

1. **Operational Data Archiving:** Systematically archive all diagnostic sessions, operator interventions, and resolution procedures with comprehensive metadata, including timestamps, operator identities, and contextual production data. Equipment data streams from standardized manufacturing protocols are preserved for longitudinal analysis and pattern recognition, enabling deep operational insights. Session metadata encompassing system states, communication logs, and environmental conditions is retained for compliance auditing and operational verification.
2. **Equipment Performance Analysis:** Machine builders and OEMs receive anonymized performance data and failure patterns through secure data sharing protocols, enabling continuous improvement in robotic design and diagnostic capabilities. Machine learning algorithms are refined through reinforcement learning based on resolution effectiveness metrics and operator feedback patterns. Predictive maintenance models undergo continuous validation and enhancement using actual failure data and intervention outcomes from production environments.
3. **Knowledge System Enhancement:** Successfully resolved incidents are systematically codified into structured troubleshooting guides with annotated solution pathways and contextual considerations. Expert operator approaches and solution methodologies are integrated into knowledge-based systems through automated pattern recognition and manual curation processes. Training curricula and certification materials are dynamically updated with real-world case studies, incorporating successful resolution techniques and lessons learned from operational incidents.
4. **Maintenance Process Optimization:** Maintenance scheduling algorithms are optimized through analysis of actual intervention data, resource utilization patterns, and production impact assessments. Equipment reliability scoring systems are continuously calibrated to

reflect actual field performance, maintenance effectiveness, and operational context variations. Resource allocation models are updated based on intervention frequency, duration, and complexity metrics across different robot types and operational conditions.

5. **Cross-Facility Performance Alignment:** Cross-facility performance benchmarks are established using aggregated resolution metrics, enabling comparative analysis and best practice sharing across manufacturing networks. Standardized performance dashboards provide unified visibility into equipment reliability, operator effectiveness, and maintenance efficiency across all production locations. Global performance trends are analyzed to identify systemic issues and coordinate improvement initiatives across the manufacturing ecosystem.
6. **Compliance and Audit Readiness:** All remote assistance sessions maintain comprehensive audit trails meeting industrial safety standards and regulatory requirements. Data retention policies ensure appropriate preservation of operational records while maintaining privacy and security protocols. Compliance reporting automatically generates necessary documentation for safety certifications, quality audits, and regulatory submissions across different jurisdictions and industry standards.
7. **Asset Contribution Log:** Records new/modified elements (e.g., refined twin models) with metadata for shared libraries, subject to governance per IDTA AAS guidelines.

Implementations and Demonstrations or Technical Feasibility

Implementations and Demonstrations

- **RoboTwin Generative Framework for Robotic Manipulation:** The RoboTwin 2.0 platform provides a state-of-the-art, generative digital twin framework specifically for bimanual (dual-arm) robotic manipulation. It leverages a large-scale object library and multimodal language models to automatically generate and validate over 100,000 expert trajectories for training robust robot policies. Its structured domain randomization across clutter, lighting, and other environmental factors has been empirically shown to achieve a 367% relative improvement in real-world performance after minimal fine-tuning, demonstrating a viable, scalable pipeline for sim-to-real transfer in remote assistance scenarios.
- **Industrial Digital Twin Deployments for Predictive Maintenance:** Siemens Energy has deployed digital twin technology for power plant simulation and maintenance prediction, demonstrating reliable virtual-physical synchronization in critical industrial environments to forecast maintenance needs and reduce downtime.
- **Production-Level Human-Robot Collaboration:** Companies like Mercedes-Benz are integrating humanoid robots, such as the Apollo model from Apptronik, directly into their assembly lines to work alongside human workers. This demonstrates the move beyond prototypes to operational systems that handle real-world manufacturing tasks.
- **Established Industrial Frameworks and Widespread Adoption:** The Industrial Digital Twin Association (IDTA) provides standardized implementation approaches, including Asset Administration Shells, which are crucial for interoperability.

Technical Feasibility:

- **Technology Convergence Foundation:** The technical foundation for remote robot assistance is not speculative but is built on the mature convergence of several proven technologies. This integration combines generative digital twin frameworks like RoboTwin, which automate the creation of robust robot behaviors, with real-time communication protocols and XR device capabilities to create comprehensive assistance systems.

- **Production Deployment Validation:** This technological convergence is actively being deployed in production environments, as evidenced by factory digital twins that integrate live data from PLCs and Manufacturing Execution Systems (MES) to optimize production scheduling and identify bottlenecks in real-time. These implementations demonstrate clear technical viability and measurable operational benefits across diverse industrial contexts.
- **Industry Adoption Evidence:** The widespread adoption of these systems provides definitive proof of their feasibility and value, with industry surveys indicating 71% of manufacturers already leveraging digital twin technologies. The resulting systems demonstrate measurable benefits—including reduced downtime, enhanced decision-making, and optimized resource utilization—across diverse industrial contexts from assembly lines to critical infrastructure.
- **Proven Architecture for Data Integration:** The MTConnect standard operates on a robust agent-adapter architecture, designed explicitly for industrial data extraction. This architecture directly enables the "standardized data collection from any device that complies with the standard" that the use case requires:
    - **Adapters Connect Directly to Data Sources:** Data sources on the equipment (such as a robot's PLC or sensors) are translated from native, proprietary protocols into the standardized MTConnect vocabulary by adapters.
    - **Agent Aggregates and Serves Data:** The Agent is a software server that aggregates data from one or more adapters and makes it available over a network in a unified, structured format (XML) via HTTP.
    - **Formal Specification and Performance Context:** This architecture is formally defined by the MTConnect Standard Version 2.5 (February 2025, with prior ANSI standardization as MTC1.4-2018 Version 1.8), ensuring vendor-neutral interoperability. It is primarily optimized for monitoring and supervisory control, with typical data exchange frequencies (1-2 Hz) being ideal for tracking machine state, alarms, and operational parameters. This performance profile is well-suited for the telemetry and status monitoring required in Remote Assistance for Autonomous Robots.
    - **Directly Addressing Monitoring Scenarios with Interoperability:** The standard is inherently designed to represent the components and data items of manufacturing equipment using a rich, semantic information model. This means a robot's coolant temperature is defined as a Temperature data item, its joint positions as Position data items, and the status of a chip hopper as an Availability or FillLevel event. The MTConnect Information Model provides the framework to describe the entire structure of the robot in a consistent, contextualized way. Furthermore, MTConnect is designed to coexist and integrate with broader industrial frameworks:
        - **Synergy with OPC UA:** In complex deployments, MTConnect's strength in extracting domain-specific data from the shop floor is often combined with OPC UA's strength in secure, enterprise-wide data modeling and transport. A common pattern uses an MTConnect-to-OPC UA Gateway, which consumes data from an MTConnect Agent and maps it into an OPC UA information model. This creates a powerful synergy where MTConnect provides the manufacturing semantics and OPC UA enables secure, reliable data transport to higher-level systems.

- **Validated in Complex, Large-Scale, and Secure Applications:** Research demonstrates that MTConnect is not only for simple machines but is validated in high-value, complex manufacturing scenarios. A peer-reviewed study successfully implemented an "MTConnect compliant monitoring system" for the finishing process of a large-scale airplane vertical tail section, involving complex data integration from machine tools, on-machine probes, and sensor-based intelligent fixtures. For such mission-critical applications, a secure implementation is paramount and is directly achievable with this architecture:
    - **Secure Implementation Practices:** By leveraging standard web technologies, MTConnect enables the use of proven security measures. A rigorous deployment must include network segmentation (e.g., placing agents in a firewalled zone), HTTPS (TLS/SSL) to encrypt data in transit, and authentication mechanisms to control client access, ensuring the entire data pipeline is protected from the adapter to the end-user application.

- **MTConnect Digital Twin Demo Validation:** The official MTConnect demo for Mazak CNC machines (using three.js AR rendering) illustrates real-time data streaming from compliant devices into an interactive 3D twin, visualizing machine status (e.g., position, temperature) in a browser-native interface. This browser-based synchronization exemplifies MTConnect's scalability for remote monitoring and assistance, bridging physical equipment data to XR visualizations without proprietary plugins, as seen in production pilots for equipment like robots.

Challenges:

- **Human Factor and Ergonomic Constraints:** Extended XR sessions induce visual fatigue and simulator sickness, requiring sophisticated comfort frameworks, session duration limits, and regular break protocols. Operators face significant skill gaps in navigating complex XR interfaces, demanding comprehensive training programs with progressive difficulty scaling and competency verification systems.
- **Network and Connectivity Requirements:** Establishing reliable, tiered network connectivity that supports both real-time control and monitoring functions while maintaining strict safety compliance across geographically distributed facilities.
- **System Integration and Synchronization Complexities:** Maintaining perfect alignment between digital twins and physical robots across variable environmental conditions presents significant technical hurdles. Ensuring consistent operation across diverse XR platforms and equipment manufacturers requires extensive standardization efforts and compatibility testing protocols.
- **Organizational and Cultural Adoption Barriers:** Many organizations perceive metaverse applications as experimental rather than strategic investments, creating resistance to budget allocation for comprehensive digital transformation initiatives. Successful implementation requires extensive cross-departmental coordination spanning IT, operations, maintenance, and training departments.
- **Data Security and Privacy Concerns:** Industrial espionage risks and cybersecurity threats necessitate robust encryption protocols and access control systems for remote

operations. Protecting proprietary manufacturing data and operational intelligence requires comprehensive security frameworks and regular vulnerability assessments.

- **Legacy System Integration Challenges:** Integrating modern digital twin ecosystems with established manufacturing equipment and control systems presents significant technical and compatibility hurdles. Migration pathways must balance operational continuity with technological advancement, often requiring hybrid interim solutions.
- **Regulatory Compliance and Standardization:** Navigating diverse international regulations for remote operations and data transfer across jurisdictions creates complex compliance requirements. Establishing industry-wide standards for interoperability and safety certification remains an ongoing challenge across the manufacturing sector.
- **Data Sovereignty & Sensitivity:** Virtual representations of proprietary operations and intellectual property in digital twins carry substantial risks of unauthorized exposure or misuse, particularly in cross-border collaborations. Addressing these demands robust, enforceable governance models with revocable access layers and comprehensive risk assessments, as outlined in ISO/IEC 27001:2022 (including Amendment 1:2024 for climate-related threats to data infrastructure).

Requirements:

Technical and Functional Requirements

- **Real-Time Synchronization:** Real-time remote assistance demands tiered network performance based on operation criticality:
  - **Tier 1 – Safety-Critical Emergency Response**
    - <50ms latency for human-initiated emergency intervention commands (controlled stop, speed reduction, safe mode activation)
    - Autonomous emergency stops for collision avoidance and immediate hazard response are handled by local robot controller per ISO 10218 safety requirements and operate independently of network communication
  - **Tier 2 – Diagnostic and Corrective Operations**
    - <50ms latency for path corrections, parameter adjustments, and fine manipulation
    - Primary operational mode for most remote assistance tasks
  - **Tier 3 – Monitoring and Visualization**
    - <100ms latency acceptable for digital twin synchronization, video streaming, and annotation sharing
  - **Bandwidth Requirements (per robot connection):**
    - Video uplink (robot → operator): 8–15 Mbps for HD, 25–40 Mbps for 4K streams
    - Control downlink (operator → robot): 2–5 Mbps for commands, telemetry, and twin state updates
    - Bidirectional jitter: <5ms to prevent control instability and operator discomfort
  - **High-fidelity operations in challenging network conditions require:**
    - Adaptive bitrate streaming with graceful degradation
    - Predictive control algorithms compensating for latency up to 200ms

- Local safety circuits at robot controller meeting ISO 10218:2025 safety requirements (typically Performance Level d per ISO 13849-1 for Class 2 industrial robots), initiating autonomous emergency stops (e.g., typical complete stop time: 100-500ms depending on robot configuration, speed, and payload)
- Redundant communication pathways:
  - Primary: Dedicated fiber or private 5G SA network with QoS reservation
  - Backup: Public 5G with priority QoS configuration
  - Failsafe: Multi-path cellular aggregation (e.g., 5G + LTE bonding)

- **Diagnostic Intelligence:** Automated unknown situation detection systems must provide confidence scoring and multi-factor prioritization of support requests based on production impact assessments. Historical pattern analysis enables rapid root cause identification through machine learning algorithms that continuously improve diagnostic accuracy using accumulated resolution data and operator feedback mechanisms across diverse failure scenarios.
- **Immersive Visualization:** Multi-modal interface support spans from basic screen displays to fully immersive VR environments, ensuring consistent information presentation across all display technologies. Intuitive gesture controls with integrated haptic feedback enable natural interaction patterns, while adaptive rendering maintains visual fidelity across different hardware capabilities from mobile devices to high-end headsets.
- **Centralized Monitoring:** Unified dashboards provide comprehensive visibility into real-time status of all robotic assets, featuring intelligent alert prioritization based on operational impact assessment and production criticality. Resource allocation optimization algorithms enable efficient handling of multiple simultaneous incidents, dynamically assigning operator expertise to maximize resolution efficiency across distributed manufacturing facilities.
- **Predictive Capabilities:** Advanced algorithms analyze historical performance data and maintenance records to enable proactive failure forecasting with recommended intervention scheduling. Continuous model refinement based on actual operational outcomes ensures increasingly accurate predictions, while integration with supply chain systems facilitates timely parts procurement and maintenance resource planning.
- **Collaborative Framework:** Multi-user support with sophisticated conflict resolution protocols enables seamless teamwork among distributed experts. Knowledge sharing systems capture and disseminate expert troubleshooting approaches, while cross-facility procedure alignment ensures consistent best practice dissemination and standardized operational methodologies across global manufacturing networks.

Interoperability Requirements

- **Standardized Data Representation:** Open digital twin standards adoption across all robotic assets ensures platform-agnostic interoperability, with mandatory fallback representations maintaining functionality across different visualization platforms. Consistent semantic definitions for equipment status and error conditions enable unified interpretation of operational data, facilitating seamless integration between equipment from multiple manufacturers and generations.
- **Unified Control Protocols:** Identical operation procedures regardless of XR device type ensure consistent user experiences through standardized input mappings with customizable user preferences. Cross-platform calibration protocols maintain consistent performance across diverse hardware configurations, while adaptive interface elements

automatically optimize for each device's specific input capabilities and interaction modalities.

Other Key Considerations:

- **Privacy**: Operator performance data, diagnostic sessions, and production information constitute protected operational records requiring granular, revocable consent mechanisms. Systems must implement automatic redaction capabilities for sensitive information and maintain strict compliance with regional data protection regulations including GDPR, CCPA per ISO/IEC 27001:2022 + Amendment 1:2024 (climate change actions).
- **Cybersecurity:** Industrial control systems (ICS) must encompass end-to-end encryption for all robot control channels, video streams, and diagnostic data exchanges. For multi-user collaboration and real-time data synchronization, channels must utilize Datagram Transport Layer Security for Secure Real-time Transport Protocols (DTLS-SRTP) aligned with ANSI/ISA-62443-2-1-2024 requirements. This core protection must be enforced by a granular, role-based access control system to prevent privilege escalation. The entire security posture must be validated through a regimen of regular vulnerability assessments and ICS-focused penetration testing conducted by certified ICS security professionals.
- **Identity Verification**: Remote assistance systems must support institutional Security Assertion Markup Language (SAML)/OpenID Connect (OIDC) single sign-on with optional decentralized identity-based ephemeral guest access for third-party experts. Multi-factor authentication becomes mandatory for sensitive content and control functions, with biometric verification required for high-risk operations involving production-critical equipment.
- **Networking & Latency**: CDN-hosted digital twin assets with adaptive bitrate 360 video streaming ensure consistent performance across varied network conditions. Priority synchronization of operational state over cosmetic elements maintains operational integrity, while offline-capable fallbacks guarantee continuous functionality during network disruptions in production environments.
- **Ownership**: Every robotic asset, digital twin component, and derived operational artifact must embed immutable provenance metadata using standardized metadata nodes or linked JSON-LD. Clear intellectual property frameworks govern created content, with blockchain-based verification available for high-value operational procedures and diagnostic methodologies.
- **Digital Ethics:** Mandated co-creation protocols with equipment operators and maintenance teams ensure ethical system design grounded in actual workplace needs. Technical access controls enforce ethical review workflows for sensitive operations, while transparent AI decision-making processes maintain accountability in automated diagnostic and intervention systems.
- **Provenance:** Complete version history of digital twin evolution and operator-generated content must be preserved as tamper-evident ledger entries. Immutable audit trails document all system modifications, intervention approvals, and procedural changes, providing comprehensive operational genealogy for compliance and continuous improvement initiatives.
- **Accessibility:** Full compliance with WCAG 2.1 AA (incorporating editorial updates through May 6, 2025) mandates keyboard navigation, screen-reader compatibility, captions for all

audio and video, support for high-contrast modes, and alternative input methods. While not a formal requirement, implementing adaptive interface complexity is a critical best practice for ensuring usability across the full spectrum of operator expertise, from novices to expert technicians.

Relevant Domain Working Group (WGs):

- Standards Registry
- Real/Virtual World Integration
- Privacy, Cybersecurity and Identity
- Network Requirements and Capabilities

Relevant Pre-qualified Organizations and Groups (POGs):

- **MTConnect Institute:** The MTConnect Institute is the central body for the MTConnect standard, which provides an open, royalty-free framework for unified data extraction from manufacturing equipment. Its working groups are highly relevant to autonomous systems, including Robotics for robot-specific data, Complex Manufacturing Systems for multi-system integration, and Agent & Open Source Tools for core software implementation.
- **International Society of Automation (ISA):** ISA provides crucial cybersecurity standards for industrial environments, most notably the ISA/IEC 62443 series developed in collaboration with IEC (latest: ANSI/ISA-62443-2-1-2024). For remote robot assistance systems, these standards mandate the implementation of a comprehensive Cybersecurity Management System (CSMS), secure development lifecycles for robot controllers and XR interfaces following ANSI/ISA-62443-4-1-2018 and the 2024 update to Part 2-1, and detailed technical security requirements for all system components including human-machine interfaces and communication networks as specified in ISA-62443-3-3:2013 and ISA-62443-4-2.
- **International Electrotechnical Commission (IEC):** The International Electrotechnical Commission establishes global standards for industrial control systems, manufacturing processes, and electrical equipment safety. Through its joint work with ISA on the IEC 62443 series and standalone standards like IEC 63278-1 for asset management federation, IEC provides the foundational electrical safety, functional safety, and control system interoperability frameworks that ensure remote robot assistance systems operate reliably across different manufacturing environments and geographic regions.
- **International Organization for Standardization (ISO):** The International Organization for Standardization delivers internationally recognized quality management ISO 9001:2015, revision DIS published August 27, 2025; FDIS expected January 2026; publication September 2026), information security (ISO/IEC 27001:2022 and Amendment 1:2024), and occupational health and safety standards (ISO 45001:2018, revision approved 2024; committee meetings began May 2025; publication ~2027) that form the backbone of reliable industrial operations. For remote robot assistance implementations, ISO standards ensure consistent quality processes for system development and maintenance, robust

information security management for sensitive operational data, and established safety protocols for human-robot collaboration environments.

- **Industrial Digital Twin Association (IDTA):** IDTA provides specialized implementation guidance for digital twin deployment in production environments through its standardized Asset Administration Shell framework. IDTA's technical specifications and implementation guidelines enable consistent digital representation of robotic assets across different platforms and manufacturers, ensuring that remote assistance systems can reliably interact with diverse equipment through standardized submodels for identification, operational data, and diagnostic information.

Relevant Specifications, Publications and Projects (SPPs):

- **MTConnect Standard:** An open, royalty-free interoperability standard designed to extract data from manufacturing equipment. Its core components—the Information Model, Data Items, and Agent/Adapter architecture—provide the universal vocabulary and data acquisition layer for modeling a robot's structure and streaming its operational data (e.g., joint positions, temperatures, availability) in a standardized XML format over HTTP (Version 2.5, February 2025 SysML enhancements).
- **Asset Administration Shell (AAS):** This specification from the Industrial Digital Twin Association (IDTA) provides a standardized digital representation for assets, serving as the cornerstone for interoperable digital twins. It encapsulates asset metadata, component relationships, operational parameters, and history in a structured, platform-neutral format, enabling seamless data exchange across systems for a comprehensive robot digital twin.
- **IEC 63278-1:2023 Asset Administration Shell Structure:** This international standard defines the core framework for creating standardized digital representations of physical assets in industrial applications (IEC 63278-1:2023). The AAS architecture is intentionally protocol-agnostic, designed to integrate data from multiple sources and standards - including MTConnect agents, OPC UA servers, MQTT streams, and other manufacturing data systems. This agnostic nature makes it critical for creating comprehensive digital twins that can unify robot operational data regardless of the underlying communication protocol or vendor system.
- **IDTA Implementation Guidelines & Submodel Templates:** These companion documents to the AAS provide practical, technical guidance for deployment in production environments. They include standardized submodel templates for specific asset aspects, which are crucial for achieving semantic interoperability for robot components, capabilities, and status within the AAS framework.
- **IEEE P3835‑2025 Digital Twin Technology Framework for Integrated Energy Systems:** Provides the architectural foundation for implementing industrial digital twins in integrated energy and manufacturing contexts. It specifies core data models, communication protocols, and synchronization mechanisms required to maintain a reliable, bidirectional connection between a physical asset (e.g., a robot) and its virtual representation. This framework is critical for enabling interoperable, scalable digital twins that unify diverse data sources (e.g., MTConnect, OPC UA, MQTT, AAS) into a coherent representation, supporting advanced applications such as predictive maintenance, XR‑enabled remote assistance, and cross‑platform asset federation.

- **IEEE 2805.2-2025 Edge Data Protocols:** Defines standardized methods for data acquisition, filtering, and buffering at edge computing nodes that interface with industrial controllers and robots. Its role is to ensure reliable, low-latency data handling at the edge, enabling consistent streams of operational data from manufacturing equipment into higher-level systems. Correction: This standard is not a digital twin framework, but rather a supporting protocol layer for edge data management.
- **RoboTwin: Remote Human-Robot Collaboration in XR (ACM HotMobile 2025):** This award-winning research publication presents a platform enabling real-time human-robot collaboration through XR interfaces. It directly validates the technical approach for remote assistance by demonstrating effective remote operation of complex robotic arms over standard internet with sub-100ms latency.
- **Systematic Review of XR-Enabled Remote Human-Robot Interaction (ACM, 2025):** This comprehensive analysis of 100 research papers provides rigorous academic validation that XR technologies significantly enhance the intuitiveness, situational awareness, and effectiveness of remote human-robot interactions in manufacturing contexts.
- **IEC Trend Report Industrial Metaverse:2025:** This report analyzes metaverse applications in industry, offering strategic guidance on the integration of XR and digital twins for remote assistance scenarios. It emphasizes the importance of interoperability with established standards like IEEE and ISO.
- **Extend Robotics AMAS Platform Case Studies:** These documented industrial deployments in automotive manufacturing (Leyland Trucks), nuclear handling, and other sectors demonstrate proven, XR-based teleoperation of robots. They showcase effective data capture pipelines that amplify human demonstrations into synthetic training data for AI, directly supporting the use case for training and remote assistance.
- **Federated Asset Information with AAS (IEC 63278-1:2023):** IEC 63278-1 defines the Asset Administration Shell (AAS) structure for industrial applications. A key architectural use of the AAS is the federation of asset information across different systems and stakeholders. This federation is enabled through registries, middleware frameworks (such as Eclipse BaSyx), and ecosystem components that unify robot data from MTConnect agents, OPC UA servers, MQTT streams, and other plant systems into a comprehensive digital twin.
- **Eclipse BaSyx Open-Source Project:** Middleware framework for implementing the AAS. Provides registries, SDKs, and connectors (Java, C++, C#) supporting OPC UA/MQTT integration. Widely adopted in research and industry for building and managing AAS-based digital twins.
- **Systems and methods of servicing equipment (US20240198979A1, pending as of November 2025):** This General Electric patent demonstrates the practical application of digital twin and metaverse principles to industrial equipment maintenance. It describes systems where robots capture environmental information for pre- and post-repair inspection, validating the concept of using robotic digital twins for remote service tasks.

Related Use Cases

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Additional Comments

- This document is a living artifact and may be subject to revisions on a periodic basis to reflect the future state of Remote Assistance for Autonomous Robots, and or based on feedback received from MSF stakeholders that warrants an update in the future.