Resilient Manufacturing Systems enabled by AI support to AR equipped operator

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Abstract*— Supply chains and manufacturing systems robustness and resilience are, for many years, but especially nowadays, key features requested to ensure reliable and efficient production processes. Two domains are crucial to achieve such purpose: the former is fast and comprehensive monitoring, efficient and reliable condition detection and effective and explicable support for decision making. The latter refers to the intervention by operators, able to better identify problems and to put in place effective operations aimed at fixing it or, better, to prevent such circumstances. This paper presents an integrated approach encompassing a sophisticated IoT and AI-based approach to monitor and detect critical situations, fully integrated with an AR (Augmented Reality) system supporting operators in the field to take informed actions in bi-directional continuous connection. Activities in the context of EC funded project Qu4lity developed in Politecnico di Milano Industry 4.0 Lab, a test environment implementing the proposed approach and demonstrating in an automated production line the effectiveness of the approach, significantly improving performances. Analysis of performance indicators demonstrates the soundness of the proposed solution and implementation methodology to make the overall production process more resilient, efficient and with product defects reduction.

***Keywords*— IIoT, AI, AR, Connected worker, Predictive Maintenance, Remote Operator Support, Human-Machine Collaboration**

I. Introduction

Industry 4.0 approach for production systems poses challenges such as operational efficiency increase, scrap reduction, prescriptive quality management, energy efficiency, defect propagation avoidance, cost and time effective zero break down sustainable manufacturing process operations, human centered manufacturing systems and brownfield deployment. That requires an orchestrated open platform ecosystem, with ZDM (Zero Defect Manufacturing) atomised components (1) and digital enablers including: Industry 4.0 digital connectivity & edge computing package, autonomous plug & control manufacturing equipment, real-time data spaces for process monitoring & adaptation, simulation data spaces for digital process twin continuity, AI-powered analytic data spaces for cognitive digital control twin services and augmented worker interventions across all phases of product and process lifecycles. This paper describes a holistic approach encompassing several platforms able to dynamically create in a brownfield environment, a flexible and effective solution. To this end a set of state-of-the-art technologies are made available based on standard platforms. The objective is also to develop faster and more precise learning loops for operators and teams in highly complex industrial manufacturing processes. A model to automatically link documentation on work execution (working operations) and how this affects the production processes (process parameters) is implemented. Visualisation for insight into individuals' and team accuracy in work performance to support learning, use of gamification to stimulate curiosity and willingness of learning is also considered.

II. Methods

The application is based on a collaborative procedure, as visible in Figure 1, in which the different steps are executed by different actors including the human worker (e.g., requested to do something), Artificial Intelligence (e.g., evaluating and making decisions if there is enough confidence in the prediction) and IoT activities (e.g., over threshold control, item presence, etc.). The modeling of the collaborative procedures is executed in Unity 3D through the Pacelab WEAVR platform (Unity 3D plugin) (2) and represented in the picture below. Complex routing can be created to support troubleshooting and steps process can be managed by variables/events (mainly from AI and IoT) or explicitly by the worker using interfaces.

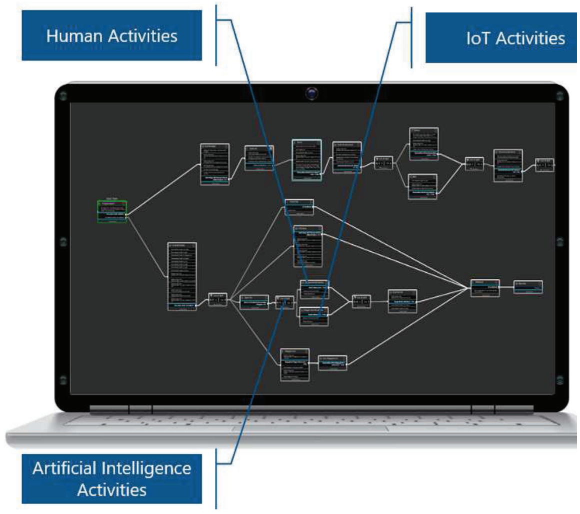

Figure 1: Collaborative troubleshooting procedure model mixing human, IoT and AI activities

The main experimentation process is the execution of a collaborative troubleshooting and maintenance on a drill bit in the production line of the Industry 4.0 Lab located in the

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Politecnico di Milano Campus Bovisa (3). Collaboration includes Augmented Human, Artificial Intelligence module and IoT-integrated operations.

The operations of the assembly line station number 2 “placing the Cover” and the number 3 “doing the Drilling” have been monitored with multiple sensors to collect further information originally unavailable like vibrations and sounds. The process includes the collection of real time data from sensors by RaspPi based boxes able to get data directly from OPC-UA modules of PLCs or from sensors connected to the machines. Subsequently collected time series are converted in JSON messages in the RaspPi and sent as MQTT Messages to the upper level for their analysis. (4)

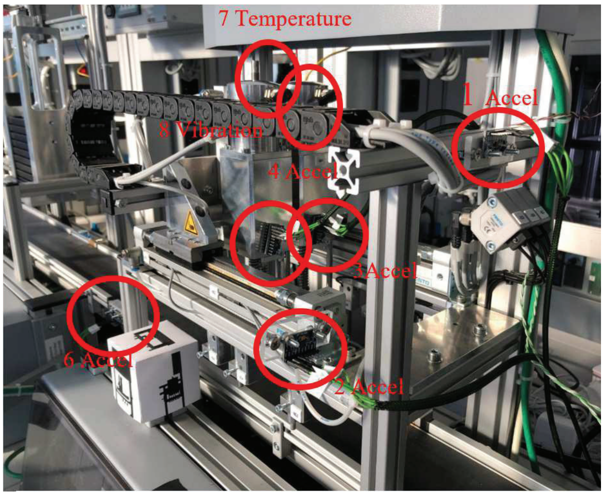

Figure 2: IOT System

Data are processed in parallel to identify the nature of the phenomena detected and anomalies are managed by a neural network trained with normal and anomalous samples (5). From a visual point of view, this information is reported on a dashboard where the results of the signal analysis for each sensor are shown for each workstation (6). Reaction is based on a combination of conditions from several sensors which allows the identification of possible complex events and to decide which action to take via decision making algorithms (7).

The interaction with user operator is carried out using Augmented Reality which has proven its potential in industry 4.0 (8) capable of reducing operators on-the-job learning curve in performing complex assembly sequences and overall tasks (9), (10), (11).

The selected Mixed Reality wearable device is HoloLens 2 (12), able to track the space around itself and make a mapping of it with sufficient precision for industrial applications (13), in order to draw a combination of 3D animations and 2D static textual or picture elements that helps anyone using it to understand better what is the assignment and how to complete it. The Augmented Worker Application (AWA), running on HoloLens, constantly receives information on the overall status of the line from the IoT and AI systems and display it to the user. In the next picture the worker perspective is provided in warning mode: top-left corner the green light shows that the connection is up and running but the yellow light shows a warning on the status of the machinery. The visible sentence “cancel order” triggers the user action immediately.

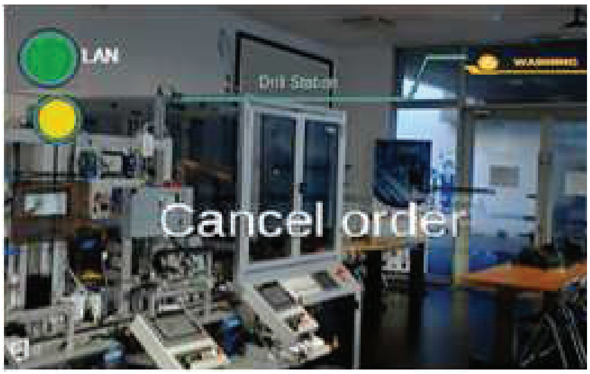

Figure 3: Augmented Worker Application (AWA) - warning

Following the alarm, a procedure is triggered. In the experimentation the troubleshooting procedure described in Figure 1 has been used to verify and solve the drill bit maintenance. The procedure provides several branches accessed depending on decisions taken and machinery status. The human worker has always a floating screen visible providing the textual instruction about the procedure step in execution; the screen can be repositioned by the human in the space for his/her convenience. As visible in Figure 4 on the target physical element, for each step, there is a set of AR contextual help for the worker including: a set of *multimedia material* (pictures and videos), *3D holograms* (e.g., arrows, circles, ISO symbols, etc.) and *IoT data* (e.g., individual sensors vibration evaluation). The information panel simplifies task comprehension, decrease errors, and speed the overall process up.

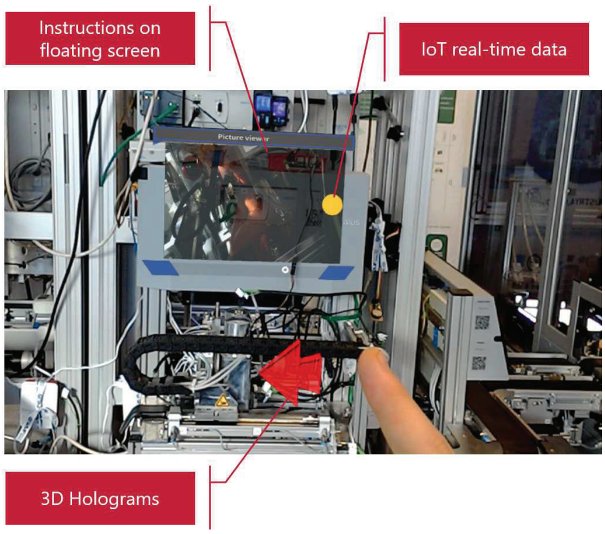

Figure 4: AWA – Augmented Reality support

In order to stress the collaboration, the experimentation has been designed to have false positive alarms which require collaboration among the actors. In some cases, vibrations simulating the drill bit performance drop are generated and easily recognized by the AI; in other cases, never before problems have now been generated including a problem on a monitoring sensor providing inaccurate data. This second category of errors are notified as warning by the AI Reasoner which is not able to discriminate the problem with adequate

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confidence interval even recognising the scenario as anomalous. A warning is provided to the operator to control the scenario. The operators have also the visibility of all the IoT data in real-time and can easily identify the sensor or sensors providing “strange” data and checking and trying to fix the connection between them correctly. To validate the operation the human worker can require, for the subsequent procedural step, to execute a monitoring test in which operators can see again in real-time the vibration data and the AI Reasoner provides a new estimation of the solutions. If the solution is found the human can close the troubleshooting, asks the AI to learn from the procedure and move to the next task.

The architecture of proposed solution was developed in the context of H2020 project QU4LITY; main components are:

- Artificial Intelligence Reasoner
- Reasoner DB / Knowledge Engine
- Augmented Reality Application (AR Core)
- WEAVR Editor
- IOT broker
- IIOT and RealTime control Interface
- Manufacturing Execution System (Interface and DB)

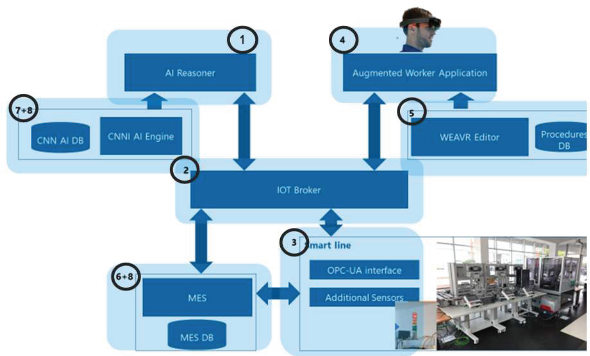

Figure 5: AWA Architecture

As introduced before, collaboration is used as leverage for making the manufacturing system resilient. This fact is also reflected in the technical architecture, in which the central element is the *IOT broker* which allows all the different architectural components to communicate the exchange information, alerts and commands. The IOT Broker communications are based on MQTT protocol which is an OASIS standard messaging protocol for the Internet of Things (IoT) (14). The choice is based on the fact that MQTT is designed as an extremely lightweight publish/subscribe messaging transport (15), (16) that is ideal for connecting most disparate devices that can be found in any manufacturing company using a small code footprint and minimal network bandwidth. The IOT Broker receives data from the smart manufacturing line, which is equipped with a set of sensors monitoring all events occurring, and publishes them through an OPC-UA interface. The Manufacturing Execution System (MES) is connected directly to the standard interface to plan and monitor the production.

Data from sensors are managed through a Decision Support System (DSS) based on Artificial Intelligence (AI) system based on a neural network which previously learned how to discover anomalies in vibrations leading to the drill bit inefficiencies. The AI Reasoner launches different kinds of alarms depending on remaining useful life and prediction confidence interval. Alarms are always sent to the broker which distributes them to the different actor including MES for recording, smart line for visual/audio alarm and to the augmented worker application (AWA) for human intervention.

The augmented worker is connected to the described system thanks to the Augmented Worker Application running on Microsoft HoloLens 2 wearable device. The HoloLens contain a Microsoft Windows 10 operating system connected to the same WiFi network of the IOT Broker. The application is based on the Pacelab WEAVR platform and is always active in the device and constantly receiving real-time data from the smart line (for example the additional sensors values) as well as the status of the monitoring of the AI Reasoner (for example the alarm status). The application contains, as major asset, a set of collaborative procedures for the realisation of activities including troubleshooting, maintenance, setup, etc. which can be executed by the worker autonomously or collaboratively with the AI Reasoner and the IOT system. These collaborative procedures have been previously modelled based on the digital twin of the system and can include different materials to support the human including CAD diagrams, multimedia material (pictures and videos) as well as 3D holograms. (17)

The architecture provided in Figure 5 is derived from the reference architecture proposed by the QU4LITY project which is provided in Figure 6. The reference architecture describes the different levels of the Zero Defect Manufacturing (ZDM) architecture and the corresponding digital infrastructure from the field to the enterprise/ecosystem level. The overlapping focuses mainly work-cell/line and at Factory levels. At production line level the overlapping is on control systems with the *IIOT and real time control interface* and the *additional sensors*. At factory level i) data driven modelling and learning services are provided by the *CNN AI engine*; ii) the digital twin and planning services are based on the *WEAVR editor* (2) modelling the *collaborative procedures* based on a factory digital twin (18) and iii) the simulation and human centric are represented by the *augmented worker application*. On the digital infrastructure the Data Lake/Big data analytics technologies are managed again by the AI infrastructure as well as the IoT Hub by the IOT Broker. At enterprise level the MES supports the operation services taking into consideration the overall results of the collaboration and performances obtained.

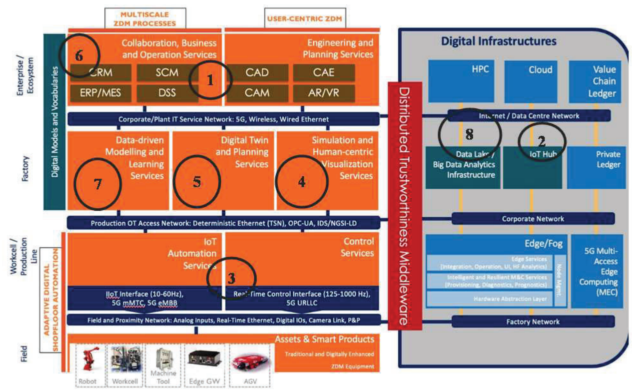

Figure 6: Mapping on Qu4lity framework

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III. FINDINGS

Experimentations executed in the Industry 4.0 Lab @ SOM Politecnico di Milano provided a number of results, bringing significant enhancements to industrial processes features. Among them we can mention the following:

1. Lot size reduction

Pilot implementation in a fully compliant environment makes any single product individually trackable and monitored, such feature allows the system a granularity in lots management both for production re-organisation and re-scheduling and condition management. Achieved results enable existing manufacturing systems to produce on average at least 50% smaller batches and at least 50% more product variations in an economical manner, so production will be demand-driven and waste will be reduced significantly. The proposed system does not preclude the possibility of unitary batch production with full tracking at the individual piece produced level of all parameters related to components and production process.

2. Set up and intervention cost optimisation

Two factors in the proposed solution impacts set-up costs and maintenance intervention: 1. Re-scheduling system minimises un-necessary production stoppage or complete change, mild interventions are suggested in case specific conditions are not such severe to impact product quality or process/ machinery integrity; 2. AR functionalities optimise operator intervention for a faster and more accurate intervention both in set-up and in repairing. Reduction of at least 30% in installation and set-up time and costs for existing production systems leading to significant increases in production capacity. Implementation of the solution is estimated at approximately 1 hour for installation, configuration and testing of each individual sensing point, including possible improvements if connection over 5G is put in place (19).

3. Energy efficiency

Reduced average energy consumption by 5% through optimised capacity utilisation is estimated. Estimated energy savings taking into account increased availability components according to OEE (Overall Equipment Effectiveness) methodology is 15% for the usage scenarios implemented.

4. System availability

Over 3000 production cycles, with simulated alarm conditions of different types (from warning to blocking) it was possible to come to 50% reduction in blocking failures. Notwithstanding the considerations on the significance of the test environment implemented at the Industry 4.0 Lab, the recognition of conditions leading to blocking faults was 80% effective, while the timely recognition of fault situations was greater than 95% with false positives of 12%. On top of that, advanced support to operators allows them to promptly identify and correct both false positive conditions and real critical case to be fixed.

5. User Collaboration success rate

Out of a total number of about 50 simulated operations we measured that 97% of operations do not require any further intervention to finalise the expected result. Reported user experience was in most cases of a satisfactory interaction with the application.

IV. CONCLUSIONS AND POSSIBLE EVOLUTIONS

Additional features enabled by the proposed solution triggered potential benefits impacting operational and business performances to be further assessed. Among them:

i. Operational enhancements
ii. Increase machinery OEE (Overall Equipment Effectiveness)
iii. Increase the efficiency and efficacy of operations (e.g.: decrease intervention time),
iv. Increase visibility on processes (everything executed is log and can be provided as input to “data mining and analytics),
v. Decrease the operator input by providing a digital decisional support to expedite the operation needed to be taken into action
vi. Increase intervention effectiveness due to high level of provided information to operator

Next steps envisaged in the research activities prosecution are:

i. Actions to support interactions with technology providers / openCall winners to integrate foreign environments in a federative fashion (20)
ii. Connection of part of sensors via 5G infrastructure. Advantage of such solution are:
    a. Wireless connection of sensors at high speed, low latency of the data transmission. This can support hard real time application or massive data transmission.

Availability of the Edge Computing platform (MEC – MultiAccess Edge Computing) for fast processing close to the plant premises.

iii. Feedback to the historical knowledge base (supporting the decision engine) of all information related to the assistance intervention carried out by the operator. This would allow to enrich the knowledge base and to improve condition management and maintenance planning.
iv. Improve wearable device based on new technology (e.g. Hololens 2, Magic Leap, …)
v. Introduce techniques of eXplainable AI support the user in the understanding of why AI did some decision to facilitate the trust the results

User experience in specific corner cases (3% as stated above) could be addressed with remote support functionalities and/or chatbot support.

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