

Perspective

Integrated Inspection of QoM, QoP, and QoS for AOI Industries in Metaverses

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Briefing: With the rapid development of information technologies such as digital twin, extended reality, and blockchain, the hype around “metaverse” is increasing at astronomical speed. However, much attention has been paid to its entertainment and social functions. Considering the openness and interoperability of metaverses, the market of quality inspection promises explosive growth. In this paper, taking advantage of metaverses, we first propose the concept of Automated Quality Inspection (AutoQI), which performs integrated inspection covering the entire manufacturing process, including Quality of Materials, Quality of Manufacturing (QoM), Quality of Products, Quality of Processes (QoP), Quality of Systems, and Quality of Services (QoS). Based on the scenarios engineering theory, we discuss how to perform interactions between metaverses and the physical world for virtual design instruction and physical validation feedback. Then we introduce a bottom-up inspection device development workflow with productivity tools offered by metaverses, making development more effective and efficient than ever. As the core of quality inspection, we propose Quality Transformers to complete detection task, while federated learning is integrated to regulate data sharing. In summary, we point out the development directions of quality inspection under metaverse tide.

Keywords: Automated Optical Inspection, Metaverses, Quality Inspection, Transformers.

I. INTRODUCTION

SINCE the year of 2019, when Facebook is rebranded as Meta, there is a metaverse fever sweeping around

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the world. Top technology companies including Epic Games, Microsoft, and NVIDIA all begin to invest and launch their metaverse projects. During the period of COVID-19, metaverse products are springing up for entertainment and social functions.

As a leading edge subject that integrates multiple information technologies, the metaverse also has superior advantages in industry field. Metaverses could provide photo-realistic, physics-based, real-time simulation environment, online collaboration platform, real-time customer communication tool, etc. These productivity tools make metaverses open up an entirely new way to develop intelligent inspection equipment in terms of hardware, software, and service.

As an indispensable part in the manufacturing process, Automated Optical Inspection (AOI) performs defect detection to realize product quality inspection. With the compact and complex Printed Circuit Board (PCB) design, corresponding manufacturing process is cumbersome, which inevitably leads to defects. These defects (including short, open, nick, etc.) would seriously affect the quality of the final product. In order to reduce the unqualified rate, defect detection is essential during manufacturing. Early PCB defect detection is conducted by human workers. With the micro size and complex layout, AOI is developed as an automated non-contact visual inspection device to replace human workers for PCB defect detection.

Because of the inaccessible and unrepeatability restrictions on data in physical world, AOI performance evaluation could not be efficiently performed in customers’ factories during manufacturing process, and this largely hinders the development of inspection devices. In this paper, we go one step further to perform integrated inspection of QoM, QoP, and QoS with a visible, interpretable, and reliable inspection performance evaluation system. Utilizing the Intelligence and Index (I&I), Calibration and Certification (C&C), and Verification and Validation (V&V) steps of scenarios engineering (SE), we perform virtual design instruction and physical validation feedback between metaverses and the physical world. Then, we propose the development process of AOI with unique productivity tools in metaverses. With these tools, engineers could explore more alternative designs in shorter time and at lower costs, meanwhile maintain a close connection with customers. Since quality inspection algorithm is the most important part of AOI, we deploy Quality Transformers to achieve better generalization performance on a wide range of inspected objects, and exploit Federated Learning (FL) to

realize data sharing while preserving data privacy.

The main contributions of our paper can be summarized into three-folds.

- We propose an integrated inspection of QoM, QoP, and QoS in metaverses. Through scenarios engineering, we build bridges between metaverses and physical world to achieve a trustworthy inspection performance evaluation, facilitating the knowledge obtained in metaverses to be applied in physical world.
- We propose the complete development process of AOI in metaverses with several productivity tools enabled by advanced information technologies, therefore pointing out the development directions of industrial production applications and tools.
- We propose Quality Transformers to achieve sustainable and trustworthy collaboration towards intelligent inspection in metaverses.

The rest of the paper is organized as follows. In Section II, we present the foundations of the metaverse and AOI. In Section III, we propose the integrated inspection of QoM, QoP, and QoS. In Section IV, we state the development workflow of AOI in metaverses. In Section V, we describe Transformers [1] and federated learning [2] as the two key technologies for AOI. In Section VI, we draw a conclusion of this paper.

II. RELATED WORK

In this section, we present the foundations of metaverse and AOI, then briefly point out the benefits of metaverses that will help overcome the obstacles to AOI development.

A. Metaverse

The term metaverse [3] originates from the science fiction novel *Snow Crash* written by Neal Stephenson in 1992. The metaverse is a virtual world parallel to the physical world, and users have their respective digital avatars to take part in recreation and competition activities. Since the development of metaverses highly relies on eXtended Reality (XR) technology, metaverses remain in their conceptional stage for a long time.

With the rapid development of digital twin [4], XR, and blockchain, metaverses have moved on to the initial practice stage. During the COVID-19 pandemic, a lifestyle shift from face-to-face meetings or gatherings to online immersive ways is happening around the world. Therefore, metaverses provide an online platform for users to work, live and play in a 3D virtual world [5]. With the enabled immersive device, such as XR headsets or glasses, users could also gain immersive experiences. Many famous companies have begun to invest and launch their metaverse projects, such as Epic Games' video games, Microsoft's Mesh, NVIDIA's Omniverse, and Meta's Horizon Worlds.

Lee et al. [6] summarize the eight key technologies for implementing metaverses and six key elements for building the ecosystem of metaverses. To access metaverses and interact with other users or objects in metaverses, XR and user interactivity is essential prerequisites. Computer Vision (CV) [7], [8], Artificial Intelligence (AI), blockchain [9], robotics, and Internet of Things (IoT) are all the key technologies

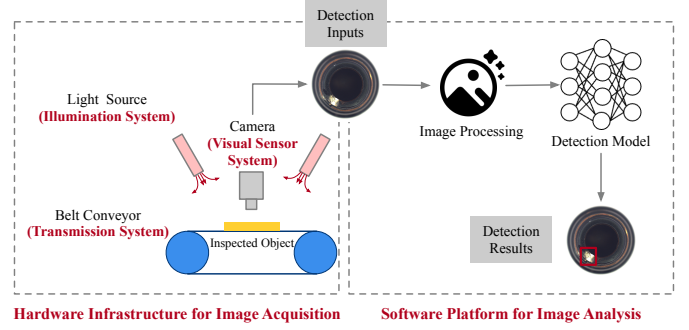


Fig. 1. A schematic of AOI in the physical world.

to implement user interactivity and XR. To conduct these operations on hardware infrastructure, rational combination of cloud computing and edge computing services [10] is designed, optimizing resource occupation rate and latency, therefore improving application performance and user experiences. For building the ecosystem of metaverses, users utilize their avatars to carry out various activities. In metaverses, content creation and its consequent virtual economy are the derivatives of these activities. When it comes to ecosystem, social acceptability, security and privacy, as well as trust and accountability should be taken into full consideration as in the physical world.

However, it is still the tip of the iceberg. With the concept of the industrial metaverse, more and more researchers and manufacturers have come to realize the significance of the industrial metaverse. Lee et al. [11] point out that, by implementing the industrial metaverse, we could decrease scrap, rework, and downtime, as well as improve productivity and training. Siemens and NVIDIA make the first attempt in industry field. They collaborate to build the industrial metaverse. With digital twins embedded technology, the industrial metaverse is expected to tackle the engineering challenges. However, there is not any comprehensive work on the specific development workflow of equipment manufacturing in the industrial metaverse, and on how to take full advantage of the tools equipped by the industrial metaverse, such as digital avatars, virtual collaboration, etc.

B. AOI

AOI is an automated non-contact visual inspection of products. AOI has a wide range of application fields including PCB industry, textile, food, etc. AOI autonomously scans inspected objects with cameras, performs image pre-processing, image analysis, and produces defect detection results. Traditional defect inspection [12] is carried out by human workers. Due to the inefficiency and error-prone shortages of manual inspection, AOI equipment [13], [14] are designed and used in manufacturing that largely replace human labor in defect detection. With the development of smart manufacturing, AOI has become an indispensable part of manufacturing process.

AOI mainly consists of two parts, the image acquisition hardware and the image analysis software. A schematic of AOI is shown in Fig. 1. The image acquisition hardware

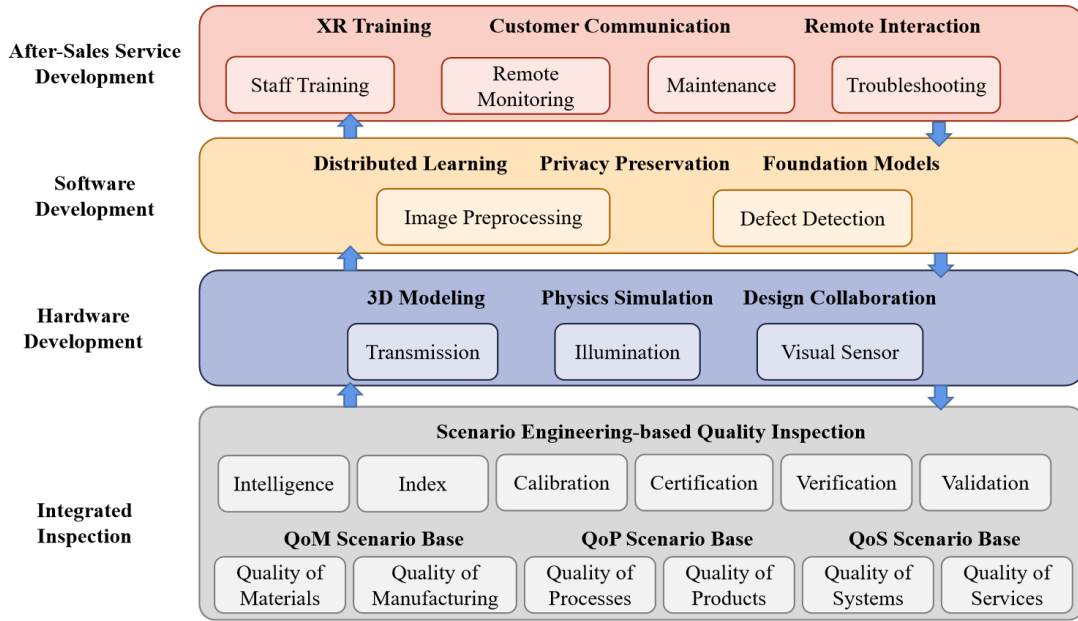


Fig. 2. The overall framework of integrated inspection of QoM, QoP, and QoS in metaverses.

is formed by three components, illumination system, visual sensor system, and transmission system. The illumination system (light sources and reflective glasses) is responsible for providing constant/customized lighting conditions. The visual sensor system (camera array) is responsible in acquiring the digital image data. The transmission system (belt conveyor) is responsible in moving PCB along the production line and completing online defect detection. Since the image quality is the essential prerequisite of subsequent image analysis, hardware structure design needs to be continuously optimized for better imaging.

The image analysis software usually has two steps, data pre-processing and defect detection. Aimed at some tough problems on hardware imaging, data processing is to perform image restoration [15], therefore provide high-quality image for detection process. AOI has already achieved quite high detection accuracy thanks to today's large-scale dataset and high-performance Deep Neural Networks (DNN) [16]. However, there are several fatal flaws that hinder the further development of AOI. For example, we could not perform structure design and corresponding simulation experiments in a seamless way [17], and could not perform effective remote instructions during after-sales service [18]. However, with data interoperability, we could perform modeling and simulation seamlessly for model-based design. With digital avatars and extended reality, we could obtain field information and make corresponding instructions.

III. INTEGRATED INSPECTION OF QoM, QoP, AND QoS

In this section, we first detail the integrated inspection [19], [20] of QoM, QoP, and QoS in AutoQI. Then, based on SE theory, we conduct I&I, C&C, and V&V, thus developing a visible, interpretable, and reliable inspection performance evaluation system, facilitating the knowledge obtained in metaverses to be applied in physical world.

A. QoM, QoP and QoS

The integrated inspection of QoM, QoP, and QoS in metaverses is shown in Fig. 2. Traditional product quality inspection is carried out by AOI. However, AOI could only perform defect detection, which covers a very limited range of potential product problems. AOI could not provide sufficient information for production optimization. Thanks to the data interoperability in metaverses, we could access and operate on production data from customers' factories and other applications. Therefore we could perform AutoQI, which covers the entire manufacturing process. With the integrated inspection of QoM, QoP, and QoS, we could track the cause of defects, prevent potential quality problems in advance, and make corresponding production improvement.

Before formal production, production processes and production systems should be determined and evaluated. For production systems, we refer to personnel operations, production facilities, and corresponding management and control [21]. After the feasibility assessment of production processes and production systems has met the demands, we could perform quality inspections on materials, manufacturing, and products by order. At last, we also perform quality inspection on the services provided by the manufacturers, which may include customer training, online support, warranty services, and upgrading services.

B. SE-based Quality Inspection

SE [22] is defined as an integrated mapping of the actual scenarios within a virtual space. Compared to features engineering, SE constructs scenario base and performs learning and testing within this base, which has much benefits in the aspect of visibility, interpretability and reliability. I&I is used to set goals (or index); C&C is used to determine suitable parameter settings and to provide a certification; and V&V is

used to validate customer requirements and to evaluate system design, performance, and functions.

Based on the SE theory, we take AOI as an example to conduct I&I, C&C, and V&V for a visible, interpretable, and reliable inspection performance evaluation system. For I&I, AOI should be equipped with “6I” at the same time, i.e., cognitive intelligence, parallel intelligence, crypto intelligence, federated intelligence, social intelligence, and ecological intelligence. And AOI should be evaluated by the indexes of “6I” for “6S” goals, i.e., safety index, security index, sustainability index, sensitivity index, service index, and smartness index. For C&C, in metaverses we could utilize digital twin technology to construct the scenario base, while calibration is conducted to assure the internal parameters in accord with physical world. And with these scenarios, certification should be issued that guarantees the corresponding functions.

Finally, for verification, we perform Factory Acceptance Test (FAT) in metaverses that meets the requirements in the order contract. In this process, we use the aforementioned scenario base to test the performance of AOI. In the scenario base, there are different kinds of actual manufacturing scenarios that will occur in the physical world. These scenario factors may contain the environmental conditions, operant behaviors, inspected objects, etc. With the combination of these factors, verification needs to conduct massive experiments. And when it fails to meet the requirements, the failure cases will be the main directions for functionality improvement.

For validation, we apply the AOI designs to the physical world. Considering the complex production environment, unexpected scenarios that are not mentioned by the order will occur. Though in very small probabilities, these unexpected scenarios could cause serious effects. Once there is a malfunction or erroneous operation of AOI, there will result in unpredictable downtime even accidents. So with validation, we contain these extreme scenarios with very small probability in our scenario base for further verification. At the same time, the failure reasons are taken into account for the next development cycle. With scenarios engineering theory, virtual-real interactions are conducted for virtual design instruction and physical validation feedback.

For other quality inspection tasks, similar steps could be done as above. However, not solely rely on visual sensors as AOI, we could integrate multiple kinds of sensors including environmental sensors, location sensors, optical sensors, and acoustic sensors to achieve data collection, and exploit Transformers to perform multi-model data fusion and analysis, thereby complete integrated inspection of QoM, QoP and QoS.

IV. AOI IN THE METAVERSES

In this section, taking AOI as an example, we show the bottom-up development workflow of AOI in metaverses.

A. Hardware Structure Design

For the hardware structure design, the ultimate goal is to achieve optimal imaging results, accordingly obtain high-quality images for subsequent detection process, thus shortening the time to perform image pre-processing. Visual sensor

and illumination system are the most significant parts should be emphasis. For illumination system, good settings could largely reduce shadow, noise, and reflection. Inspected object size, color, surface feature, geometry, material, and environment are all key factors to be considered in selecting the right light source, positioning, incident angles, etc. For visual sensor system, good settings could reduce blur, overexposure, and low-contrast. Common settings of cameras need to be fine-tuned include the extrinsic parameters and internal parameters. The extrinsic parameters refer to location and orientation. The intrinsic parameters refer to parameters such as focal length, aperture, field-of-view, resolution, etc. In addition, the coordination of illumination and visual sensors should also receive attention.

In current AOI design process, though there is a certain accumulated experience from development engineers, hardware design still highly relies on massive experiments in the physical world to test various possibilities, and select the experimental settings with the best performance as hardware prototype for next version. However, this process always spends months to years, and costs huge development investment to find out a better solution. Furthermore, considering the customization demand from different inspected objects, there are expensive communication costs.

With the advanced digital twin technology, which includes 3D modeling, virtual reality [23], and computer graphics, a 3D design environment could be built in metaverses. In this design environment, engineers could also conduct comprehensive physics experiments such as structural and optical mechanisms with the designed structure. Engineers could perform AOI hardware system simulation as a whole, combining the parameter settings of illumination, visual sensors, and transmission, making the coordination of different parts of hardware infrastructure. Though there are already several design tools such as SolidWorks and simulation tools such as Multiphysics, the features provided by them are still very limited and the operations of these tools are quite complicated. For example, the modeling process of hardware structure and corresponding physical properties cannot be inter-connected; The design and simulation process needs a large volume of complex initializations; The simulation functions cannot cover common phenomena such as parameter drift. These all make development engineers prefer actual physics experiments.

In addition, this design environment in metaverses enables developers to collaborate with customers and colleagues to complete the design. On the one hand, the collaborative work has no distance limitation caused by pandemic or any other cases. On the other hand, customers could easily join the development process with a feeling of presence through personalized avatars and immersive experiences.

In summary, this collaborative design environment largely saves development investment, shortens development cycle, and improves customer satisfaction.

B. Software Platform Optimization

Inspection task is the core of AOI. Current AOI highly rely on large-scale dataset to solve the poor performance on unseen

data. However, current data collection could only be done when AOI encountering failures on defect detection. Since, on the one hand, the order of inspected objects usually is confidential, which means data collected by a third-party (AOI supplier) is forbidden. On the other hand, there are no safety data sharing policies that could secure the data privacy while data transfer.

To solve these problems, we propose to exploit federated learning to realize data sharing while preserving data privacy. Federated learning is a distributed training policy that performs gradient transfer rather than data transfer, thereby avoiding privacy leaks. In addition, the ownership of the data possessions between buyers and suppliers in metaverses is worth heeding. We could deploy blockchain technologies in metaverses. Blockchain is based on decentralized and distributed ledger database which provides traceable and distributed solutions for data recording and management. By using private and public keys mechanism, blockchain grants data producers corresponding ownership. In this way, third-party intermediaries could not misuse data and gain profits without the permission of data owner. In the meantime, data owners have the ability to authorize third-party to access their data. Moreover, during the use of data, we could exploit decentralized autonomous organization (DAO) with smart contracts to regulate the cooperation and benefit allocation between multiple parties. DAO is a new paradigm for management of organizations where each member has the right to propose and decide the rules and policies for the operations of the community.

With the above mentioned data sharing policy, there will be large-scale datasets for use. Due to the remarkable representation ability, we could use Transformer model to complete inspection tasks. Transformers could complete pre-training on massive unlabeled data in a self-supervised way and then be fine-tuned on labeled small-scale task-specific data. Transformers largely alleviate the burden of data annotation, while achieving the state-of-the-art performance. Further content is detailed in the next section.

Moreover, to maintain secrecy, production factories are not usually connected to the Internet. Therefore, traditional AOI software upgrading is performed by offline retraining and then deployed on customer devices. With the application of distributed privacy-preserving policy, AOI could perform online training, which guarantees much-faster response speeds of failure cases and achieve software upgrading.

Therefore, the data sharing software platform improves data utilization, generalization performance, and response speed.

C. After-Sales Service Improvement

As an important part of AOI product, after-sales service has not been paid more attention to. Nevertheless, after-sales service is fundamental to customer retention, and sometimes could result in soaring costs. In metaverses, with the development of the immerse capabilities including visual, audio, haptic feedback, we could perform XR training, remote interaction, and remote instruction, thus making it possible for engineers to complete remote monitoring, troubleshooting, maintenance, staff training, etc. Therefore, workers do not need to stay in the factories all the time.

For XR training, compared to on-site training, the AOI platform provides a safe virtual training environment, where all the operations could be repeated and reset. In addition, when workers conduct dangerous erroneous operations that may cause accidents, the platform will demonstrate the corresponding dire consequences, e. g., workers will get real pain from haptic feedback, which might stick in their memory. Engineers could be more mentally focused in the XR environment with no distractions. For remote interaction, multi-modal data (e.g. audio, visuals, smell, and haptics) generated in inspected object factories can be sent back to the cloud center of AOI supplier in real time. These information can be recorded and analyzed as valuable data source, especially when a failure happens.

Therefore, the remote interaction platform raises training quality, reduces potential danger, achieves real-time response, and improves customer satisfaction.

V. ORGANIZATION AND INTELLIGENT INSPECTION FOR METAVERSES

In metaverses, tremendous and diverse data can be obtained based on emerging technologies such as DAOs and blockchains [9], [24]. DAO-based collaboration provides a distributed and democratic way to maintain the operations of the community. Valid members in the community have the right to initialize a proposal and others can vote to pass it or not. Passed proposals will be executed automatically using smart contracts. To stimulate the participation of members, blockchain-based incentive mechanisms are introduced to reward beneficial actions like contributing data resources. DAO-based approaches protect the ownership and income rights of members, which lay the foundation for sustainable AOI ecology.

Considering that Transformer models have long-range dependence and dynamic modeling ability [25], we utilize them to build the inspection models for quality evaluation. With the massive data in metaverses, the proposed Quality Transformers can be designed with a large capacity to increase the representation ability and generate foundation models [26]. Transfer learning technologies can be applied to adapt the foundation models to smaller ones for different applications. Besides, with federated learning methods [27], privacy can be maintained during the development of inspection models. [28].

A. Multi-Source and Multi-Model Inputs for Quality Transformers

Data resource is the foundation for intelligent inspection systems with data-driven approaches. With metaverses, much more diverse information in the production lines can be obtained compared with traditional physical factories. The advantages of information flow in metaverses can be summarized as follows.

- Flexible spatial range. Constrained by the installation locations and angles, only a small amount of data can be collected by physical sensors, which will hinder the comprehensive inspection of the production processes. In metaverses, virtual sensors like cameras and LiDAR can

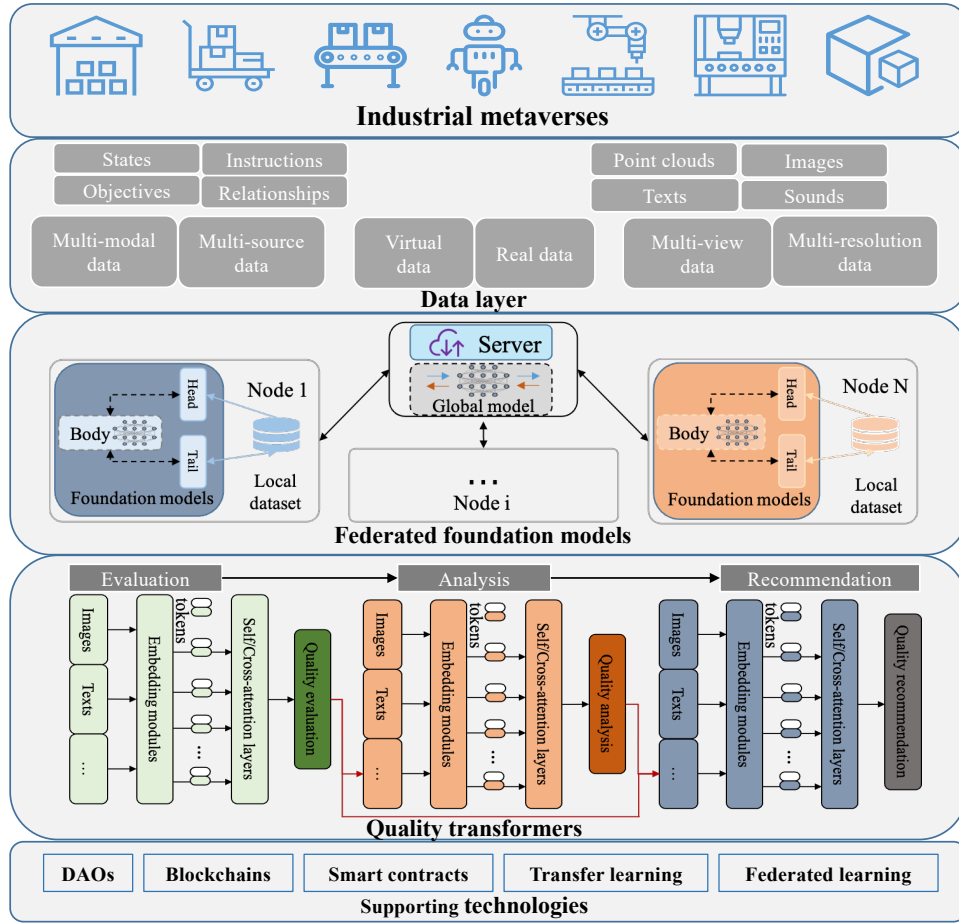


Fig. 3. The framework of Quality Transformers in metaverses.

be flexibly adjusted and configured, multiple sensors can be adopted to provide multi-view, multi-resolution data about the real-time manufacturing process.

- **Multi-modal inputs.** Images of products, scalar data of device parameters as well as environmental information dominate the inputs for inspection in traditional manufacturing processes. In metaverses, different modalities of data can be easily obtained, such as the texts, sounds, gestures as well as actions, to transform the description of states to the description of scenarios.
- **Real-virtual mixed data.** The combination of virtual and real data is another characteristic of metaverses. For the defects found in the real world, massive virtual data can be simulated in metaverses to quickly increase the amount of data with a similar distribution.

B. Quality Transformers

With massive and diverse data, comprehensive and intelligent models can be constructed. Towards the full pipeline of production and selling, three kinds of Transformers are included in metaverses for quality evaluation, quality analysis, and quality recommendation inspired by the parallel theory [29], [30], as shown in Fig. 3.

Quality Evaluation Transformer (QET) focuses on specific aspects of the whole industrial process, such as products,

manufacturing processes, and services. It takes images, videos, voices, or texts as inputs, and adopts self-attention and cross-attention to aggregate useful information and evaluate different local modules in the industrial processes. Typical tasks of QET include product defect detection and service scoring.

Quality Analysis Transformers (QAT) are designed to overall consider the industrial processes based on the evaluation results from QET and the states of machines, digital humans, and the manufacturing environment. QAT predicts the possible reasons behind the quality issues. To develop QAT, massive computation experiments can be conducted in metaverses to generate virtual failures for industrial processes thus building the database for the diagnosis of quality degradation.

Quality Recommendation Transformers (QRT) provide suggestions for the improvement of quality. With metaverses, knowledge and operations from experienced human workers can be easily stored which provides the possibility to transform human insights into intelligent models to automatically search for optimal strategies to improve production quality. Factors to be considered in the recommendation process include the states of machines and workers, the representation of the objectives as well as the outputs from QET and QAT.

C. Foundation Models with Federated Learning

Instead of developing inspection models for each enterprise individually, we propose to aggregate the resources from multiple organizations to further improve the scale and diversity of data. Therefore, the privacy leakage issues should be considered. Towards flexible adaptability to diverse tasks and privacy-preserving collaboration, we adopt federated learning approaches to develop the quality foundation models. To incorporate diverse inputs from the industrial scenarios, different single-modal transformer blocks are designed to learn and encode the features from different domains such as states of the manufacturing process, instruction from workers, relationships among different working nodes as well as the data from sensors. Then cross-modal transformer blocks network are used to fuse multiple features and generate the representation for final tasks. The foundation models can be trained with self-supervised approaches or with the virtual data generated from metaverses to avoid the expensive annotation cost.

To utilize the data resource from different nodes and avoid the privacy leakage, federated learning methods can be applied in the development of foundation models. One global model is shared among all the participants, and then local updates are aggregated in the server node to iteratively generate new global models. In case of some participants have limited computing or storage resources, the global model can also be splitted into several parts with small heads, big bodys and small tails [31]. The head and tail part are used to prevent privacy leakage from both the raw inputs as well as the annotations. The information flow on the heavy body can be conducted on the server part. To further protect the information safety during the transmission process, privacy computation methods like secure multi-party computation and homomorphic encryption can be deployed.

VI. CONCLUSION

In this paper, we propose integrated inspection framework with development workflow and core algorithm in metaverses. We first introduce integrated inspection of QoM, QoP, and QoS on the whole manufacturing chain. Taking AOI as an example, we clarify the I&I, C&C, and V&V steps to realize the inspection performance evaluation based on the scenarios engineering theory. With the advanced information technologies in metaverses, we propose a bottom-up workflow for hardware, software upgrading, and after-sales service improvement. As the core technology of inspection task, we propose Quality Transformers and utilize federated learning to regulate data sharing. In conclusion, with the benefits of metaverses, we extend product quality inspection to integrated inspection, which could be the future development trend for industrial manufacturing.

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