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A Framework for Cloud Inspection of Complex Mechanical Parts

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ABSTRACT Inspection plays an important role in quality control and trust of manufacturing service in the cloud manufacturing (CMfg) paradigm. To provide an inspection service for complex mechanical parts in CMfg, the concept of cloud inspection was defined as a multi-dimension extension of CMfg. A framework of cloud inspection consisting of the physical resource layer, the cloud inspection platform, and the application layer was constructed. The data model of cloud inspection, including the role model, resource model, and business model was constructed. Besides, a 4-phrase process model was built by integrating digital inspection technology into the cloud manufacturing environment. Inspection resources including hardware resources, software resources, and knowledge resources were connected to the cloud inspection platform. A four-level model was proposed for the encapsulation of inspection services. Enable toolsets for cloud inspection of complex mechanical parts, including the inspection planning toolset, measurement programming toolset, inspection process monitor toolset, and data analysis toolset were encapsulated. A prototype system was developed. A case study was given to verify the effectiveness and feasibility of the proposed framework. The framework for cloud inspection provides a solution for the inspection business of mechanical parts in CMfg.

INDEX TERMS Cloud inspection, cloud manufacturing, data model, process model, complex mechanical part.

I. INTRODUCTION

Mechanical parts with complex structures are widely used in transportation products such as automobiles, ships, and airplanes. Complex mechanical parts have the characteristics of high requirements of precision, complex processes, expensive raw materials, and difficulties in quality control. Traditionally, the manufacturing of complex mechanical parts has required substantial investment in resources for processing, inspection, and quality assurance. The relatively recent development of cloud manufacturing (CMfg) has brought a new solution to the production of complex mechanical parts. CMfg is a new service-oriented manufacturing paradigm [1]. Researchers have proposed various architectures for the CMfg platform [2]. However, they all follow a basic modeling route, which involves constructing a unified model of manufacturing resources (including hardware, software, and manufacturing expertise) in the physical world. Using internet of things (IoT), web services, and virtual machines, the manufacturing resources are connected to the cloud platform. In the cloud platform, the manufacturing resources are encapsulated and manufacturing services are published [1]–[5]. Through the CMfg platform, the manufacturing service demander (MSD) publishes the manufacturing demands. With the support of intelligent matching algorithms, the appropriate manufacturing service providers (MSP) are recommended to the MSD. The MSD and MSP accomplish the manufacturing process collaboratively via the cloud platform. CMfg has advantages in the optimal configuration of manufacturing resources and coordination of manufacturing processes [3]. The MSD of complex mechanical parts can receive satisfactory manufacturing services from the CMfg platform. Without the need to build a complete production line, the cost of manufacturing investment can be reduced significantly.

The trading of manufacturing services in the CMfg platform is internet-based trading. Compared with traditional e-commerce businesses, the trade of manufacturing services for complex mechanical parts is usually characterized by complex processes, a long production period, and a large number of transactions. Thus, quality and trusted manufacturing services are especially important for the implementation of the

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CMfg paradigm. To solve the problem, studies about trust and quality of service (QoS) were carried out. Xie *et al.* proposed a trust management model with a comprehensive degree of trust composed of direct trust, indirect trust, and the weight of overall trust assessment, which provides a more dynamic and comprehensive trust model [6]. Yan *et al.* proposed a trust model from direct trust, indirect trust, ant third-party trust. In their work, the quality of product was considered as a component of direct trust [7]. Yang *et al.* constructed a trust model based on data of the cloud service user satisfaction [8]. Li *et al.* proposed a framework of a trust evaluation system and an evaluation model oriented to mechanical manufacturing [9]. In their work, trust is evaluated in terms of time control, economic efficiency, processing quality, service attitude, business scale, and logistical effectiveness. Lou *et al.* brought quality and reliability to the comprehensive trust model, which is based on applying the objective quality state of products to the trust model of manufacturing services [10].

In all these proposed trust models [6]–[10], the data on product quality is the important component of objective trust, which relies on inspection technology. In the conventional manufacturing paradigm, the inspection activities and acquisition of data on quality are usually executed by the quality control (QC) and quality assurance (QA) department of a company. However, in CMfg, remote inspection based on the cloud platform becomes possible. With the CMfg platform, the MSD can inspect the products by using a third-party inspection service, through which more objective data on quality can be acquired. Therefore, an inspection enabler is needed in CMfg, and as one of the key QA technologies, inspection is essential in CMfg.

The application of inspection technology to CMfg requires studies about resource modeling, service encapsulation, system framework, and data and process modeling. Similar to other cloud services technologies, such as cloud design, cloud process, and cloud simulation, cloud inspection can be considered as an expansion and application of CMfg-facing inspection context. The earlier studies of cloud design, cloud simulation, cloud machining, and cloud three-dimensional (3D) printing laid the foundation for cloud inspection. For example, Chen, *et al.* demonstrated an innovative service model of the cloud design platform and proposed a method of crowdsourcing the optimal combination and scheduling of members to improve the efficiency of cloud design [11]. Zhang, *et al.* proposed a cloud-based 3D printing service platform based on CMfg [12]. Wu *et al.* proposed characteristics and requirements for cloud-based design and manufacturing systems [13]. Zhang *et al.* developed a 3D printing cloud service platform and proposed a cloud 3D print task modeling architecture for complex networks based on the dynamic coupling of nodes to deal with the problem of inefficient resource allocation [14], [15].

These studies imported the business context and the technologies of the current manufacturing paradigm to the CMfg environment. Studies on system platforms, algorithms, and frameworks were conducted. CMfg services facing different manufacturing contexts were built. Compared with these cloud services technologies, such as cloud design, cloud 3D printing, and cloud simulation, inspection in CMfg has specific needs. The model for cloud inspection is different from that of other cloud services due to the independence and objectivity of inspection data. The information model of cloud inspection resources and cloud inspection capabilities is also different from that of the other cloud services. The cloud inspection service requires special service functional toolsets as well. Therefore, more studies on cloud inspection are needed.

To summarize, inspection is one of the key technologies of CMfg. However, the existing research about inspection in CMfg is inadequate. In previous works [16], the authors proposed a basic concept of cloud inspection and imported model-based definition (MBD) inspection technology into CMfg. Based on previous work, a more concrete concept model of cloud inspection (CInsp) was proposed, and the framework, data model, and process model of CInsp were constructed. A prototype system of CInsp was also developed. A case study based on an application of CInsp to a mechanical part was conducted to verify the effectiveness of the proposed framework.

The remainder of the article is organized as follows. The concept model of CInsp is proposed in Section 2. In Section 3, the framework, data model, and process model of cloud inspection are introduced. A prototype system of cloud inspection is discussed and a case study is described in Section 4. Section 5 provides the discussion and conclusions.

II. CONCEPT MODEL OF CLOUD INSPECTION

The concept of cloud inspection was proposed in our previous work [16]. A more concrete concept model is shown in Fig. 1.

In this model, the CInsp consists of CInsp roles, CInsp platform, and CInsp resources. CInsp roles include CInsp service provider, CInsp platform operator, and CInsp service consumer. The CInsp service providers connect their inspection resources, including inspection devices, inspection software and system, and the inspection knowledge to the CInsp platform. The CInsp platform operator is responsible for the construction and maintaining of the CInsp platform. The CInsp service consumer publish their inspection requirements based on the CInsp platform. CInsp services are accessed by system matching or interactively selecting. Besides, the CInsp service consumer can participate in the cloud inspection process with the CInsp platform. The CInsp platform consists of the data layer, the service layer, and the operation layer. The related information of cloud inspection was formatted and modeled in the data layer. Inspection resources are encapsulated as CInsp toolsets. Different toolsets such as inspection plan toolset and data acquisition toolset are combined and encapsulated as CInsp services. The operation layer is responsible for the information and process management and the integration with other systems. In general, cloud inspection is defined from the followed aspects.

(1) CInsp is a product life cycle enabling tool. CMfg is designed to provide tools for product life cycle activities,

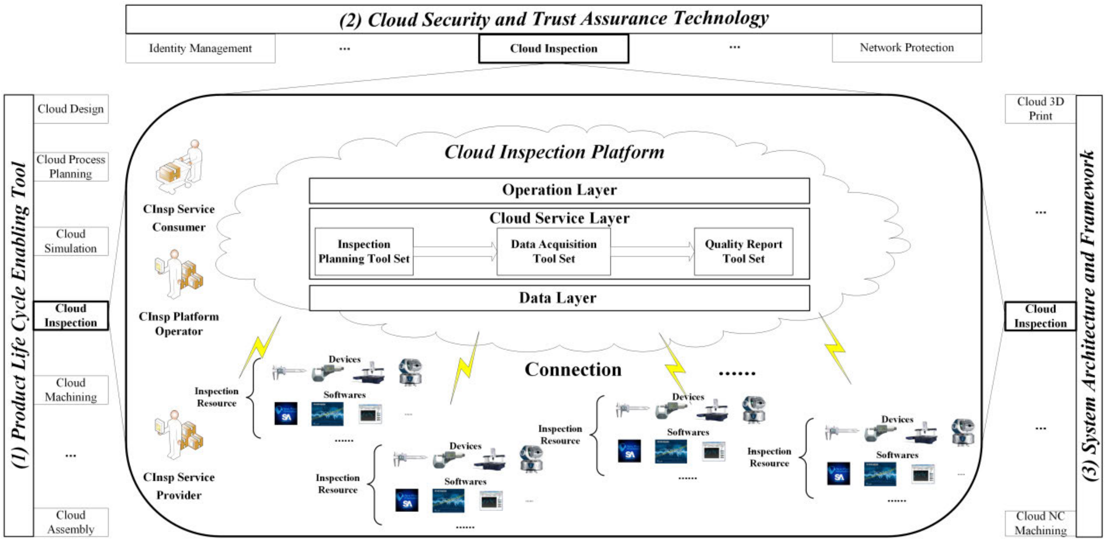


FIGURE 1. Cloud inspection as multi-dimension Extension of CMfg.

such as cloud design, cloud process planning, and cloud simulation. Inspection is a key activity in product life cycle, making cloud inspection a tool in the CMfg environment for enabling inspection activity by integrating an inspection system, inspection resources, and inspection capability into the CMfg platform.

(2) CInsp is one of the support technologies for cloud security and trust assurance. As discussed in Section 1, trading in CMfg is internet-based trade. Therefore, security and trust assurance technology, such as identify management and network protection, are essential for the operation of the CMfg paradigm. Cloud inspection is a trust assurance technology that collects data on product quality and provides basic data for the evaluation of objective trust of manufacturing services.

(3) CInsp is an extension of CMfg. CMfg is a complex multi-level manufacturing system [1]–[4], [18]. Cloud inspection is a subsystem of CMfg. Based on the basic structure and framework of the CMfg platform, a cloud inspection platform was constructed by connecting the inspection resources, expanding the data model and process model of digital inspection, and encapsulating a cloud inspection service.

III. THE FRAMEWORK OF CLOUD INSPECTION

The framework of CInsp was constructed according to the concept of cloud inspection. As shown in Fig. 2, the cloud inspection framework consists of the physical resource layer, the cloud inspection platform, and the application layer.

1) PHYSICAL RESOURCE LAYER

The inspection resources belong to CMfg resources and are divided into hardware resources, software resources, and knowledge resources, according to the classification of CMfg resources in the study by Zhao [19]. Each type of inspection resource is limited by its inspection capability. Hardware resources include the inspection devices and tools, such as the coordinate measurement machine (CMM) and laser scanner, which are used to verify product quality. The inspection capability of hardware resources is determined by measurement range and measurement accuracy. The measurement range belongs to the built-in attribute. The measurement accuracy belongs to the dynamic attribute, which needs periodic calibration and analysis. Software resources include the inspection software and system used in inspection processes, such as the inspection planning system, CMM programming software, and inspection data acquisition software. The inspection capability of the software resources is determined by the data interface of the software and the precision of the data analysis algorithms. Knowledge resources include the experiences and rules used to improve the efficiency and reduce the risk of misoperation in the inspection process. Knowledge resources are usually organized in the form of a knowledge base. The inspection capability of knowledge resources is defined by the applicability of the knowledge base.

2) CLOUD INSPECTION PLATFORM LAYERS

Trading in the cloud inspection platform requires the combination of software resources, hardware resources, and knowledge resources. In the cloud inspection platform, physical inspection resources are connected to the cloud platform. With further encapsulation, a series of cloud inspection toolsets are set up. The cloud inspection service assembles the cloud inspection toolsets in a logical manner, and then establishes the data model and process model of cloud inspection. On the one hand, the correlation of information objects, such as cloud inspection demands, inspection resources, inspection capabilities, and inspection activities, is described in a unified data model, which is the basis of cloud inspection. On the other hand, the information flow and workflow are described in the process model, which is the process basis of cloud inspection. In the proposed framework, the cloud inspection platform is composed of the following modules.

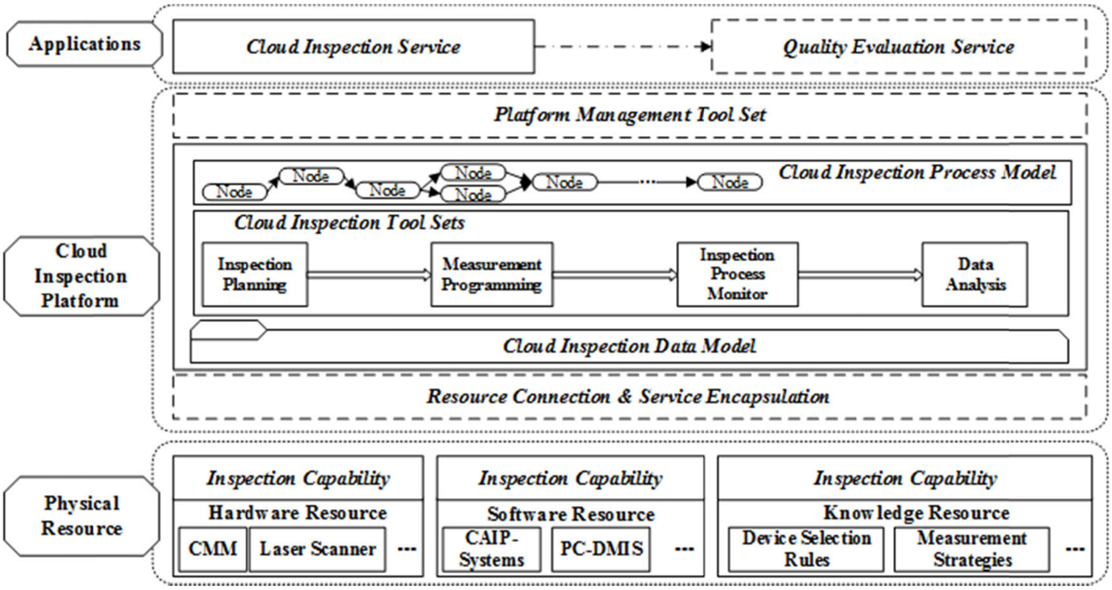


FIGURE 2. The framework of cloud inspection.

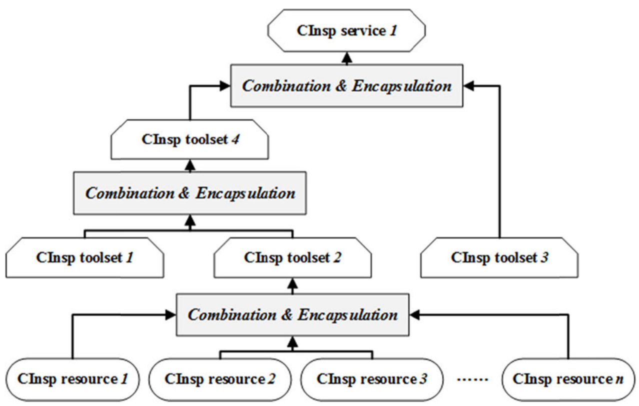


FIGURE 3. Encapsulation of CInsp service.

➢ **Resource Connection & Service Encapsulation**

The connection of cloud resources and the encapsulation of cloud services are the keys to cloud inspection. As shown in Fig. 3, an encapsulation model with a three-level structure was put forward in this article to provide a unified structure for the encapsulation of cloud inspection services.

Three particle sizes of the data object—CInsp resource, CInsp toolset, and CInsp service— are defined. A CInsp resource is a map of physical inspection resources. After connecting to the cloud platform, the physical inspection resources are defined as CInsp resources. The CInsp toolset is composed of a single or multiple CInsp resources in terms of specific rules. Similarly, a CInsp service is composed of single or multiple CInsp toolsets in terms of specific rules. By defining the correlation and data exchange rules of low-level components, a high-level component was encapsulated. Based on the modeling method, a three-level encapsulation model was constructed.

➢ **Cloud Inspection Data Model**

The cloud inspection data model is the data and organization basis of the cloud inspection platform. The data model of cloud inspection defines the data structure and the correlation of information items in cloud inspection, including cloud inspection users, cloud inspection resources, cloud inspection businesses, and cloud inspection services. The data exchange structure between cloud inspection processes is also defined in the data model. The cloud inspection data model is constructed from four aspects: cloud inspection user, cloud inspection resource, cloud inspection business, and objective trust. This will be discussed in Section 3 Part A.

To to prevent conflict and missing data, a multi-level digital object identifier data structure was built for the data management of CInsp platform, as shown in Fig.4. The data structure consists of CInsp task level and CInsp Result level. In the CInsp task level, the business data objects consist of CInsp plan, CInsp item, CInsp geometry feature, measuring point. Based on the digital inspection business data model [18], there is one effective inspection plan for one mechanical part. An inspection plan consists of several inspection items. There is a many-to-many relationship between inspection items and geometry features. Besides, a geometry feature, such as a plane or a cylinder needs several measuring points to finish the inspection task. Based on the relationship of inspection plans, inspection items, geometry features, and measuring points, digital object identifiers including CInsp plan ID, CInsp item ID, CInsp geometry feature ID, measuring point ID were set up as the digital identifiers for CInsp task data.

In the CInsp result level, the inspection business data was organized based on the mechanical part. Based on the digital inspection business data model [18], there are several inspection item results in one mechanical part. With the many-to-many relationship between inspection items and geometry features, the specific measuring points of one inspection item could be found. Thus, three particle sizes of digital object identifiers, including mechanical part ID, CInsp item result ID, and point result data ID was set up.

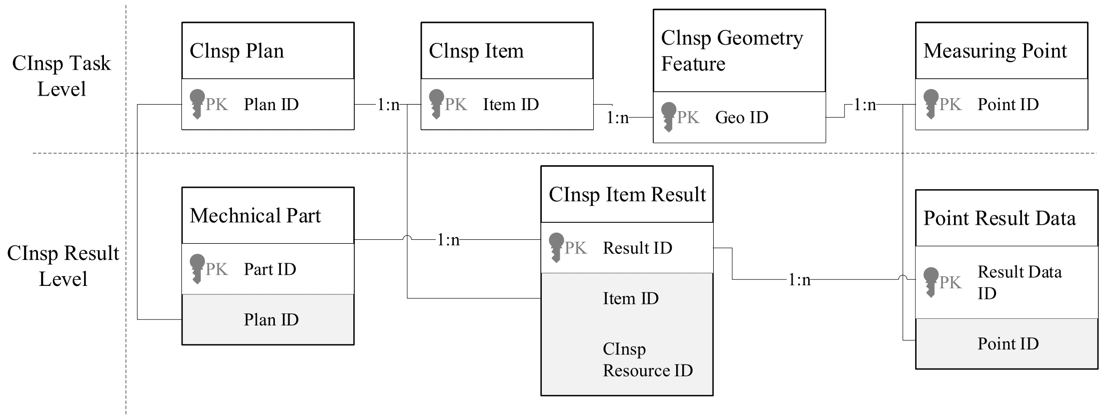


FIGURE 4. Multi-level digital object identifier.

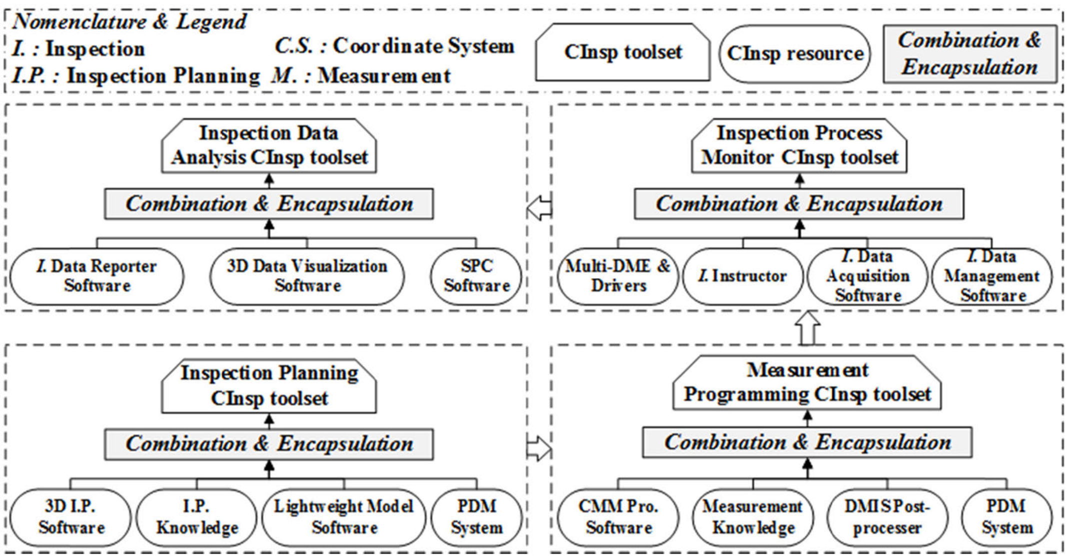


FIGURE 5. Cloud inspection toolsets in the proposed framework.

Besides, the relationship between the CInsp task level and the CInsp result level was constructed. Connections between the CInsp plan ID and mechanical part ID, the CInsp item ID and item result ID, and the measuring point ID and point result ID were built separately. Thus, the data objects in CInsp were identified and connected.

➢ **Cloud Inspection Toolsets**

The CInsp toolset consists of a series of CInsp resources based on particular rules. In the proposed framework, the CInsp toolsets are encapsulated to accomplish the inspection of mechanical parts in the CMfg environment.

As shown in Fig. 5, CInsp toolsets the this system include the following.

Inspection Planning Toolset: 3D inspection planning software, inspection planning knowledge, lightweight model software, and the product data management (PDM) system are encapsulated into the inspection planning CInsp toolset. Based on this toolset, a 3D inspection plan can be established and published. The input of the toolset is the MBD model of the mechanical part. The output is the published 3D inspection plan.

Measurement Programming Toolset: CMM programming software, online measuring machine (OMM) programming software, measurement programming knowledge, Dimensional Measuring Interface Standard (DMIS) post-processor, and PDM system are encapsulated into the measurement programming CInsp toolset. With this toolset, the measuring program for mechanical parts can be defined and managed in the cloud platform. The input of the toolset is the MBD model of the mechanical part. The output is the published measuring program.

Inspection Process Monitor Toolset: Multi-dimensional measuring equipment and its drivers, inspection instructor, inspection data acquisition software, and inspection data management software are encapsulated into the inspection process monitor CInsp toolset. This toolset is responsible for driving the inspection hardware resources, the execution of inspection, and the acquisition of quality data. This toolset allow the CInsp service consumer to monitor the inspection execution process in real-time based on on-line video. The inspection data were managed in the CInsp platform.

Inspection Data Analysis Toolset: Inspection data reporter software, 3D inspection data visualization, and analysis software, and statistical process control (SPC) software are encapsulated into the inspection data analysis CInsp toolset. In this toolset, the quality data are analyzed and visualized based on the 3D model of mechanical parts. A report on the quality of mechanical parts with a 3D model is generated as well. The statistical analysis of quality data is also available in this toolset.

➢ **Cloud Inspection Process Model**

The cloud inspection process model defines the information flow and workflow of the cloud inspection platform. The process model is constructed by fusing the business process model of digital inspection and the cloud service operation model. The process model will be discussed in detail in Section 3 Part B.

➢ **Platform Management Toolset**

The platform management toolset is responsible for the management of the roles, users, resources, toolsets, cloud service, data, and process of the cloud inspection platform, for the purpose of ensuring the operation of cloud inspection. The integration of the cloud inspection platform and other information systems is also implemented in this toolset.

3) APPLICATION LAYERS

The cloud inspection services exposed to CInsp service consumers are encapsulated in the application layer. In the proposed framework, the cloud inspection service and objective trust evaluation service are defined. The data from cloud inspection service can be the input of objective trust evaluation serivice, which is an key support of trust management in CMfg.

A. DATA MODEL OF CLOUD INSPECTION

The data model of CInsp is constructed from four aspects: role model, resource model, business model.

1) ROLE MODEL

CInsp expands upon CMfg by applying digital inspection technology to the CMfg environment. Thus, the role model follows the basic framework of the role model in CMfg[1]. The role model in cloud inspection consists of CInsp service consumer, CInsp service provider, and CInsp platform operator.

- CInsp service consumer: A CInsp service consumer is a role in cloud inspection that has requirements for business inspection or evaluation of objective trust and obtains cloud inspection services on demand and in time with the support of the cloud platform. A CInsp service consumer in cloud inspection can be an MSD who needs to verify the products or an MSP who lacks inspection resources.
- CInsp service provider: A CInsp service provider is a role in cloud inspection that provides inspection resources and capabilities as cloud services by the cloud inspection platform. A CInsp service provider can be an MSP or an MSD or even a cloud manufacturing platform operator (CMPO). However, the CInsp service provider in a cloud inspection service cannot be the same MSP who produced the products to be inspected. The principle guarantees the independence and objectivity of the inspection data.
- CInsp platform operator: A CInsp platform operator is a role that is responsible for the operation of the cloud inspection platform. As cloud inspection is an extension of CMfg, a CInsp platform operator is usually a CMPO in the CMfg platform.

2) CLOUD INSPECTION RESOURCE MODEL

A unified model for various inspection resources was proposed. A CInsp resource is described as a quaternion {RID, RDescription, RAbility, RData}:

A CInsp resource is defined by four data items: (i) The RID of CInsp resource consists of the ID and URL. The RID is generated when the CInsp service provider registers the CInsp resource in the cloud inspection platform. With the RID, the CInsp resource can be accessed and applied to the cloud inspection process. (ii) The RDescription of CInsp resource is the built-in information of CInsp resource, including the type of CInsp resource, and the instruction of CInsp resource. (iii) The RAbility of CInsp resource is composed of the input datatype, output datatype, measurement range, measurement precision, and the result of measurement system analysis (MSA), including bias, stability, linearity, and repeatability & reproducibility (R&R). (iv) The RData of the CInsp resource belong to dynamic attributes. The data structure of RData is defined by input and output datatype in RAbility.

3) CLOUD INSPECTION BUSINESS MODEL

The cloud inspection business model in this article is built for the process of cloud inspection of mechanical parts. With preview work about model-based integrated inspection [17] and MBD technology in the cloud manufacturing environment [16], the cloud inspection business model is constructed based on the MBD model of mechanical parts. The inspection requirements are integrated into the MBD model. An inspection item is generated based on an inspection requirement and connected with CInsp resources. The inspection plan is composed of inspection items. For an inspection task, an instance of the inspection plan is generated. The inspection data can be integrated into the MBD model based on the identification of inspection items and the RID of the CInsp resource.

B. PROCESS MODEL OF CLOUD INSPECTION

As a fusion of CMfg and digital inspection, the process model of cloud inspection is presented in Fig. 6.

PROCEDURE 1: PUBLISHING DEMAND & SERVICE ENCAPSULATION

In this step, the inspection resources provided by CInsp service providers are connected to the cloud platform through the IoT or virtual machines. The CInsp platform operator encapsulates the resources and publishes the cloud inspection services. The CInsp service consumers publish the inspection

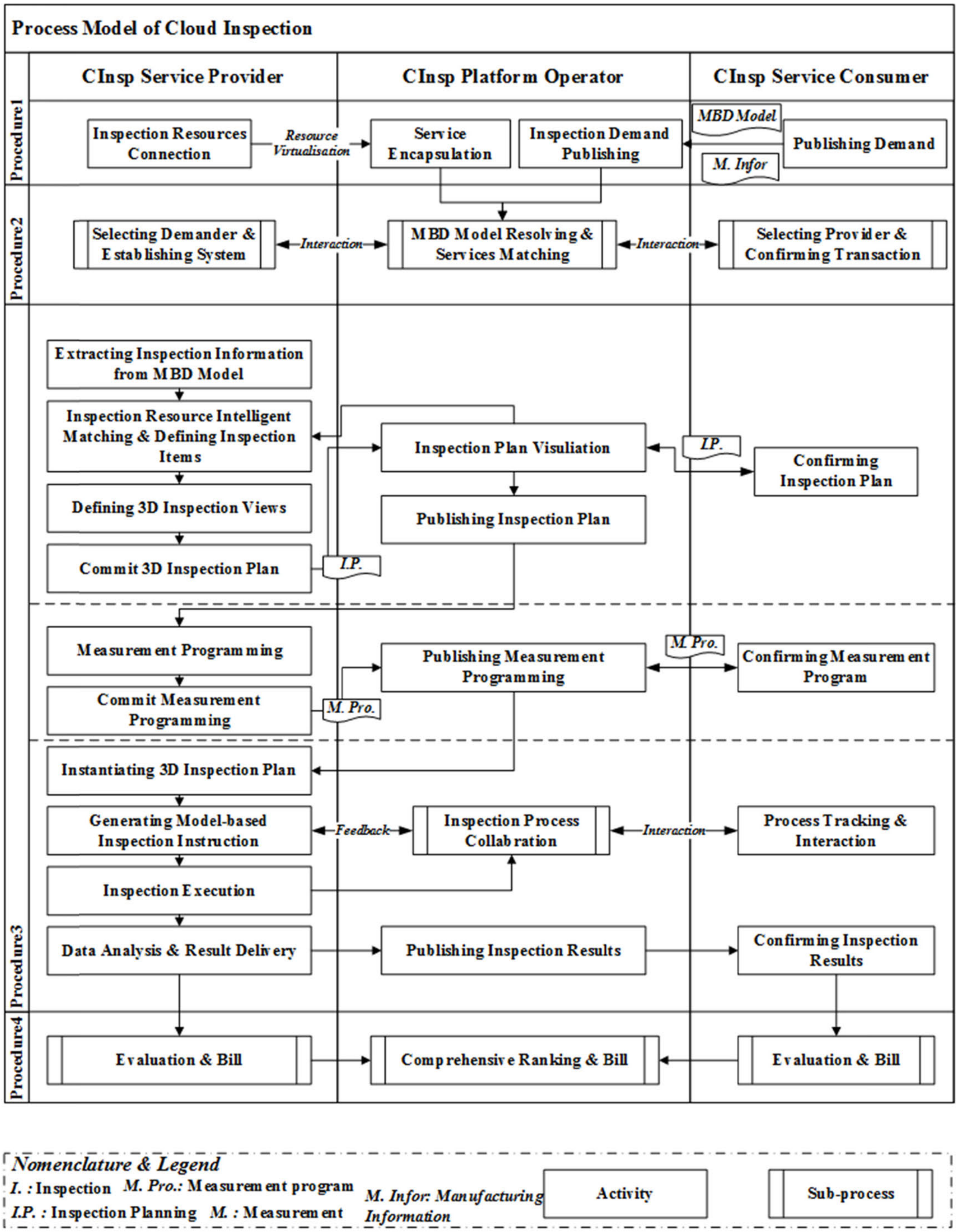


FIGURE 6. Process model of cloud inspection.

demand by uploading the MBD model and manufacturing information to the cloud platform. The CInsp platform operator publishes the cloud inspection demand.

PROCEDURE 2: CLOUD INSPECTION SERVICE MATCHING

The MBD model and the manufacturing information are extracted and formatted in this step, in which the inspection demands are transformed into normalized and structured data. The inspection knowledge from the inspection planning process is used in this step to support the inspection service matching for the CInsp service consumers. In Step ii, the relationship between CInsp service consumers and the CInsp service provider is established.

PROCEDURE 3: CLOUD INSPECTION SERVICE EXECUTION

The cloud inspection service execution is a four-step inspection planning process, in which the CInsp service provider and CInsp service consumer can complete the cloud inspection process collaboratively with the cloud platform. It includes the following steps:

(i) Inspection planning step. In this step, the CInsp service provider obtains the MBD model from the CInsp platform operator. Then, with the inspection planning CInsp toolset, the CInsp service provider extracts the inspection information from the MBD model of the mechanical part. Supported by the inspection planning knowledge resource, the inspection resources are matched intelligently and the inspection items are defined. For each inspection item, a 3D inspection view in the MBD model is generated. The inspection plan is published in the cloud platform for the CInsp service consumer to confirm. The identification system is constructed, based on which every inspection item and inspection feature can be tracked throughout the cloud inspection process. With the identification system, the inspection data are trusted.

(ii) Measurement programming step. In this step, with the measurement programming CInsp toolset, the measurement program based on the inspection plan is generated. In addition, the identification of inspection items and inspection features is encapsulated into the measurement program. The CInsp service provider and CInsp service consumer can work together in the programming process via the cloud platform.

(iii) Inspection execution step. In this step, the inspection plan and measurement program are transferred from the cloud platform to the CInsp service provider. With the inspection process monitor CInsp toolset, model-based inspection process instruction is generated. Based on the identification of the inspection plan and measurement program, real-time inspection data are acquired accurately. In addition, the off-line inspection process is monitored, with a CCTV system via the cloud platform. The inspection results are delivered to the cloud platform and confirmed by the CInsp service consumer.

PROCEDURE 4: EVALUATION & BILLING

After completing the service, the CInsp service provider and CInsp service consumer each gives a comprehensive evaluation to the other. According to the charging rule defined, a bill will be generated automatically. This procedure is similar to the final procedure of most e-commerce activities.

IV. CASE STUDY

A prototype system of cloud inspection was developed and a case study was conducted to demonstrate the application of cloud inspection. The MBD model of the selected mechanical part is shown in Fig. 7.

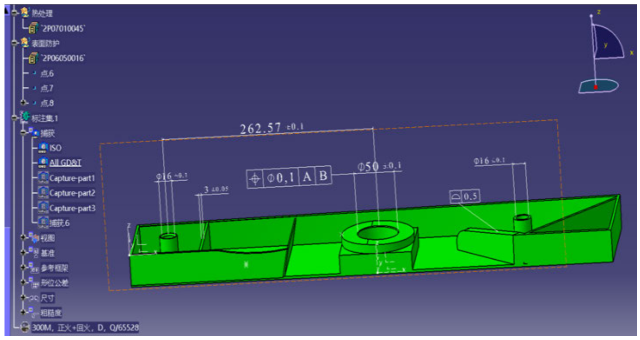


FIGURE 7. The MBD model of the selected part.

A. DEMAND PUBLISHING

As shown in Fig. 8, the manufacturing information and the MBD model of the parts were uploaded to the cloud platform by the CInsp service consumer. Next a cloud inspection demand was generated in the platform. The specific demand information would be accessed by resolving the MBD model and manufacturing information, using the CInsp toolset to resolve the MBD model. The product manufacturing information (PMI), geometry and topology information, process route, and process parameters were used to match with the suitable CInsp service provider. Once the the CInsp service provider is confirmed, the cloud inspection can be conducted collaboratively through the cloud platform.

B. CLOUD INSPECTION PLANNING

Cloud inspection planning is the start of the cloud inspection process. As shown in Fig. 9, with the inspection planning CInsp toolset, the inspection demands in the resolved MBD model were extracted. The 3D annotations and related geometry features were transformed to formatted inspection requirement information. With the inspection knowledge encapsulated in the CInsp platform, the inspection plan was generated automatically. The type and value of 3D annotations, the geometry feature types, and the geometry feature parameters were input to the inspection knowledge toolset. Then the inspection tools, inspection methods, and inspection parameters were recommended. As shown in Fig. 9, the 3D inspection plan was transmitted to the cloud platform. Through the CInsp platform, the CInsp service consumer has access to the formatted inspection plan with a 3D lightweight model. After being confirmed, the 3D inspection plan would be published in the cloud platform as the execution order of this inspection task.

C. COLLABORATIVE MEASUREMENT PROGRAMMING

Based on the inspection plan, the geometry features that need to be measured by CMM and OMM were extracted with the measurement programming CInsp toolset, as shown in Fig. 10. Through the toolset, measuring coordinate systems were constructed based on datum features, as shown in Fig. 10(a). The common algorithms for constructing measuring coordinate systems were encapsulated in this toolset, such as reference datums method, iterative method, best fit method, etc. In this case, the two datum holes and one datum plane were selected to build the measuring coordinate system. With the methodologies encapsulated in the CInsp toolset, the sampling measuring points of the geometry features to be inspected and a collision-free measurement path were generated, as shown in Fig. 10(b) and Fig. 10(c). After path planning, the measuring information was delivered to the cloud inspection simulation tool. Based on the simulation tool, the measuring points and position points were extracted. The CMM in the simulation environment was driven. Fig. 10(d) shows the measuring process simulation. The CInsp service

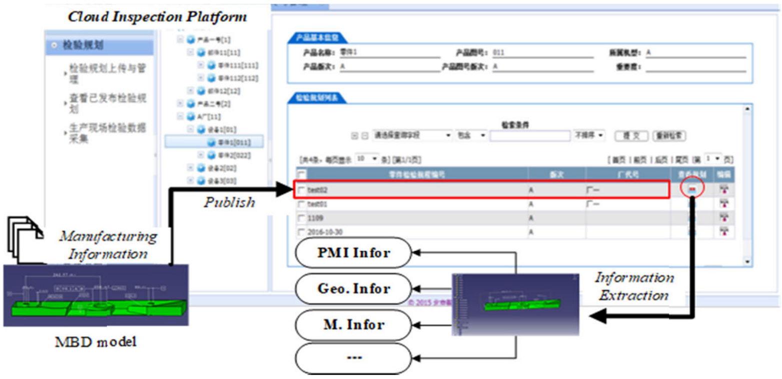


FIGURE 8. Case Study 1: Demand publishing.

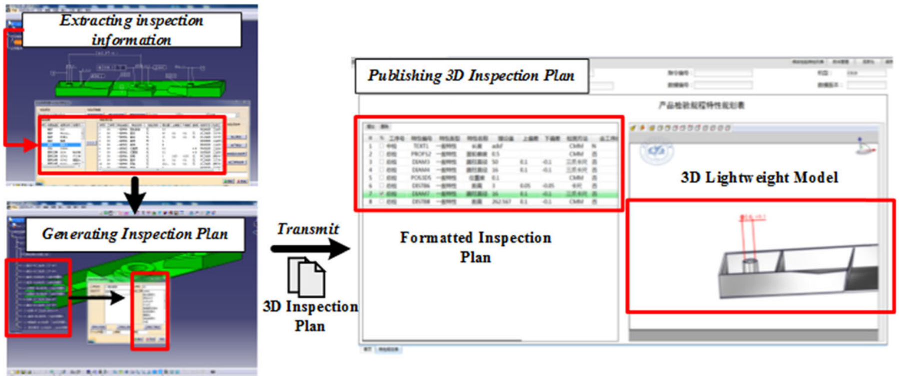
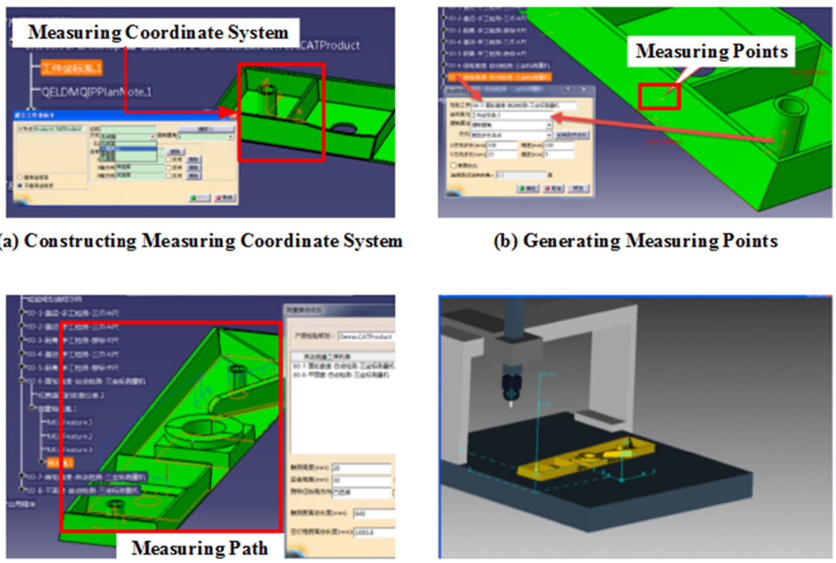


FIGURE 9. Case Study 2: Inspection planning CInsp toolset.



(a) Constructing Measuring Coordinate System
(b) Generating Measuring Points
(c) Generating Measuring Path
(d) Measuring Process Simulation

FIGURE 10. Case Study 3: Measurement programming CInsp toolset.

consumer could monitor the programming process through the cloud inspection platform. After verified by the CInsp service consumer, the measurement program for the part was published in the cloud platform.

D. COLLABORATIVE INSPECTION EXECUTION

After the CInsp service consumer confirmed the inspection plan and measurement program, the mechanical parts were delivered to the CInsp service provider. The inspection process was executed off-line but collaboratively. As shown in Fig. 11, an inspection monitoring CCTV was built in this case to provide real-time video of the inspection execution process. The CInsp service consumer have access to the real-time status of the cloud inspection task based on the on-line video. For the inspection execution process, the inspection task was allocated and the model-based inspection

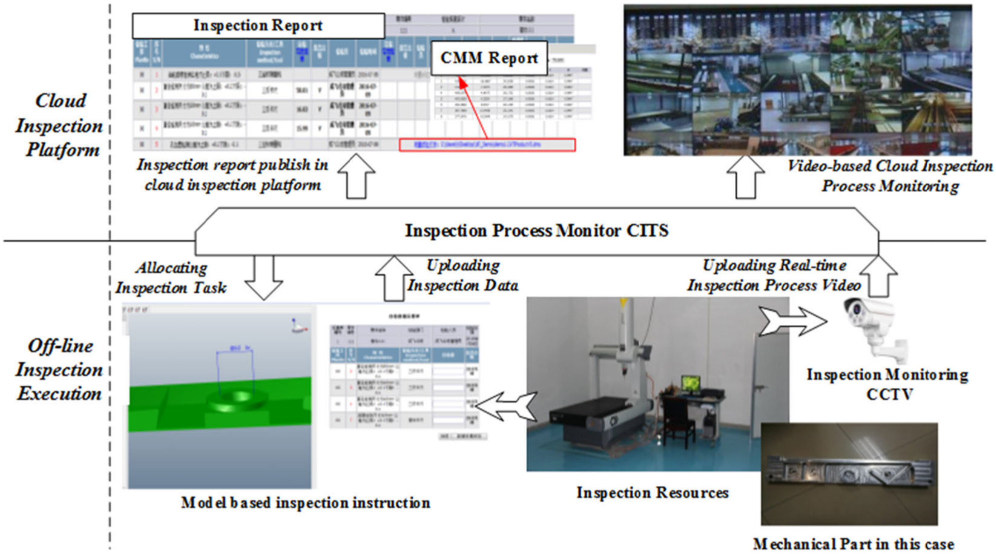


FIGURE 11. Case Study 4 & 5: Off-line insepction execution and uploading inspection data.

process instruction was generated based on the 3D inspection plan with the inspection process monitor CInsp toolset. The inspection data were collected and uploaded to the cloud inspection platform.

E. INSPECTION RESULTS PUBLISHED

After finishing the inspection process, the inspection results, as well as the CMM and OMM reports, were published in the cloud platform, as shown in Fig. 11. The CInsp service consumer can review the inspection report, as well as the original CMM report. Once the results were confirmed, the mechanical parts were delivered back to the CInsp service consumer.

V. CONCLUSION AND DISCUSSION

In this article, the concept, framework, data model, and process model of CInsp are introduced. CInsp is an expansion of cloud manufacturing by importing digital inspection technology into the cloud environment. The framework of cloud inspection was built from the physical resource layer, cloud inspection platform, and application layer. The framework of cloud inspection follows the basic structure of cloud manufacturing and has a unique architecture for the inspection business. The data model of cloud inspection is constructed from four aspects: role model, resource model, business model, and objective trust model. The role model inherits the role model of cloud manufacturing. The resource model is an expansion of the manufacturing resource model. The business model is the reconstitution of the model-based inspection business model in the cloud environment. The process model of cloud inspection is the fusion of the process model of digital inspection and cloud manufacturing. A prototype system was developed and a case study was conducted. Through the case study, the application of cloud inspection was demonstrated and the effectiveness of the proposed framework was verified. The proposed CInsp framework provided a solution for the inspection business of complex mechanical parts in CMfg. Based on CInsp platform, the CInsp service consumer can finish inspection tasks using remote inspection resources provided by CInsp service providers. The inspection process is executed collaboratively. The inspection data were delivered in-time. Besides, the inspection data of mechanical parts in the cloud platform could be taken as the basis of trust models for manufacturing services.

In this article, the framework of CInsp was proposed. However, there are more works of CInsp worthy of further studies, such as more enabling toolsets for different inspection contexts. The CInsp toolsets proposed in this article were developed for mechanical parts. However, with the extensive application of cloud manufacturing, such as 3D print in cloud manufacturing, assembly in cloud manufacturing, etc. The CInsp toolsets for different inspection contexts should be also encapsulated into the CInsp framework to expand the application of CInsp platform.

VI. ABBREVIATIONS

Abbreviations	Explanations
CInsp	cloud inspection
CMfg	cloud manufacturing
MSD	manufacturing service demander
MSP	manufacturing service provider
CMPO	cloud manufacturing platform operator
CMM	coordinate measuring machine
OMM	online measuring machine
PMI	product manufacturing information
MSA	measurement system analysis
R&R	repeatability & reproducibility
MBD	model based definition
QC	quality control
QA	quality assurance

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