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Development of a Digital Twin and Digital Thread Model for Quality Inspection of Machined Parts via On-Machine Measurement

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Abstract
This study proposes a STEP (ISO10303 AP242)-based digital twin and digital thread model for the quality inspection of machined components, enabling rapid feedback and data connectivity in quality management. The framework is designed to be utilized not only with CMMs but also for on-machine measurement in machining centres. The quality inspection digital twin consists of quasi-static synchronization of measurements, calculation of quality inspection results, a visualization model for measurements, and dimensional error compensation. For the on-machine measurement, dimensional and geometric tolerance inspection results are calculated by receiving the measured coordinate data and tolerance information from the machining centre's user variables into the digital twin. Each inspection result is assessed to determine whether it falls within tolerance limits and is visualized along with the CAD/GD&T data in the STEP file. Additionally, by utilizing dimensional tolerance data, the system can indirectly estimate dimensional errors caused by tool wear and includes a function to compensate for the tool diameter. The quality inspection digital thread consists of CAD/GD&T information extraction, measurement path generation, and storage of inspection results. GD&T data (such as tolerance levels and surface information) is extracted from STEP information, followed by the automatic generation of probe measurement paths to assess tolerances. After measurement, the probe results (3D coordinates) and tolerance types are transmitted via industrial communication protocols, and inspection results are stored. The digital transformation of quality data exchange is expected to enable rapid communication between suppliers and customers, significantly reducing time for process improvement.

Quality Inspection, On-machine Measurement, ISO10303 AP242, Digital Thread, Digital Twin, GD&T

1. Introduction

Standards such as STEP (Standard for the Exchange of Product model data, ISO 10303 AP242) and QIF (Quality Information Framework, ISO 23952) are being established to enable data exchange across various design platforms by utilizing MBD (Model-Based Definition), which defines PMI (Part Manufacturing Information) of a part based on its 3D geometry data[1,2]. Geometric and dimensional tolerances (GD&T) are critical quality-related information within manufacturing data. In the Model-Based Definition (MBD) paradigm, these tolerances are represented as annotated information in 2D/3D drawings to reflect customer requirements. These tolerances are primarily inspected using three-dimensional measuring machines (CMMs). Typically, PMI information (GD&T data) and measurement results (inspection data) are managed separately. The QIF standard addresses this issue by establishing a standardized model for integrating and exchanging inspection data. However, STEP is still widely used as a product MBD standard, but it is not connected to quality inspection. As a result, CMM inspection results are managed either in proprietary data formats of CMM software or as separate electronic documents. Therefore, a digital thread model that can link STEP information with quality results is required.

Research on utilizing digital threads with a focus on quality in manufacturing has been actively conducted in recent years. Zhang [3] proposed a digital twin framework based on a digital thread for real-time prediction and optimization in aircraft assembly processes, presenting examples of improvement through process and quality prediction/analysis at each stage. Similarly, Lee [4] proposed a digital thread for machining, integrating not only quality data from STEP but also CAM, virtual machining, and process monitoring signals to enable correlation analysis in cutting operations.

Machine probes in machine tools are primarily used to set workpiece coordinates or measure the offset of rotational axes. Recently, with advancements in the precision and volumetric accuracy of machining centers, on-machine measurement using probes has been increasingly applied to measure and correct geometric errors in machining centers and to inspect critical dimensions and contour accuracy[5]. On-machine quality inspection allows immediate verification of critical tolerances and error correction within the machine, thereby enhancing the reliability of quality management. However, solutions and data formats for on-machine quality inspection vary among probe manufacturers and solution providers, with limited connectivity to CAD/GD&T information. Consequently, there is a lack of use cases and research on digital threads and digital twins for on-machine quality inspection.

This study proposes a digital thread model for on-machine measurement, inspection result generation, and mutual analysis in machining centers, utilizing CAD and GD&T information based on the STEP standard. Furthermore, a quality management approach is presented by implementing a digital twin model that allows immediate measurement, quality monitoring, and correction of machined parts after processing, leveraging the digital thread.

2. Digital Twin and Digital Thread for Quality Inspection via the On-machine Measurement

The proposed digital thread and digital twin for on-machine quality management are implemented through the procedure demonstrated in Figure 1. The digital thread for quality management digitizes and extracts GD&T information from the STEP file. Based on the extracted data, it generates on-machine inspection paths, taking into account the type of machining center controller. Upon completion of the inspection, the inspection result data is stored in the database along with the part model information. This allows for cross-referencing of part models, GD&T data, inspection programs, and inspection result data, thereby enhancing data connectivity and reusability.

The digital twin for quality management utilizes the part model and inspection programs generated through the digital thread to conduct inspections and visualizes the quality in physical terms at designated intervals. Additionally, by monitoring quality and analyzing dimensional deviations caused by tool wear, the digital twin can update tool diameter and length compensation values directly to the machining center. To enable this, bidirectional communication between the machining center and the digital twin is essential. Once all GD&T inspections are completed, the inspection results for a single machined part are output in the format of the digital thread's inspection result data. For ease of explanation, a simple injection mold, as shown in Figure 2, is used as an example.

3. Quality Inspection Digital Thread Model

3.1. GD&T information extraction

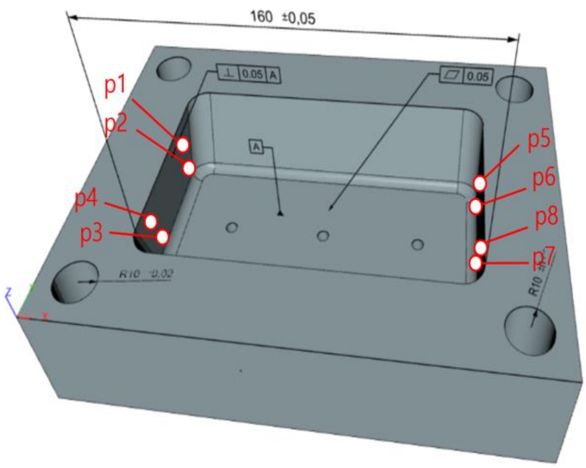

Figure 2. PMI(GD&T) information in the MBD for a simple injection moldThe first step in the digital thread for quality inspection is the extraction of GD&T data, including tolerance information and geometrical features, from the MBD part data. In this study, various types of data, such as tolerance values, surface properties, and geometric features, are extracted using the STEP format for neutral application. The extracted GD&T information is stored in JSON format, primarily consists of `gdt_data_ID`, `rel_cad_data_ID`, processing timestamp (`update_date`), and `gdt_info`, which contains the GD&T details. Inside `gdt_info`, tolerance items are managed in an array format, with `num_gdt` representing the total number of GD&T items. Each item is stored in the `gdt_item` array, and the key components are as follows. `gdt_definition_entity` stores a unique entity number from the STEP file, while `geometric_tolerance` defines the type of tolerance. The description field provides an explanation of the tolerance, and magnitude represents the measurement unit. The `geometric_information` to which the tolerance applies is provided through the `toleranced_geometry` field, which includes `detailed_shape` characteristics via `shape_aspect` and `advanced_face`. Specifically, the `detailed_definition` field contains the GD&T type (`gdt_type`), the normal vector (`normal_vector`), the sign of the geometric tolerance (`sign`), the reference vector (`reference_vector`), and the number of measurement points (`num_feature_point`), along with their respective coordinates (`point1`, `point2`, etc.).

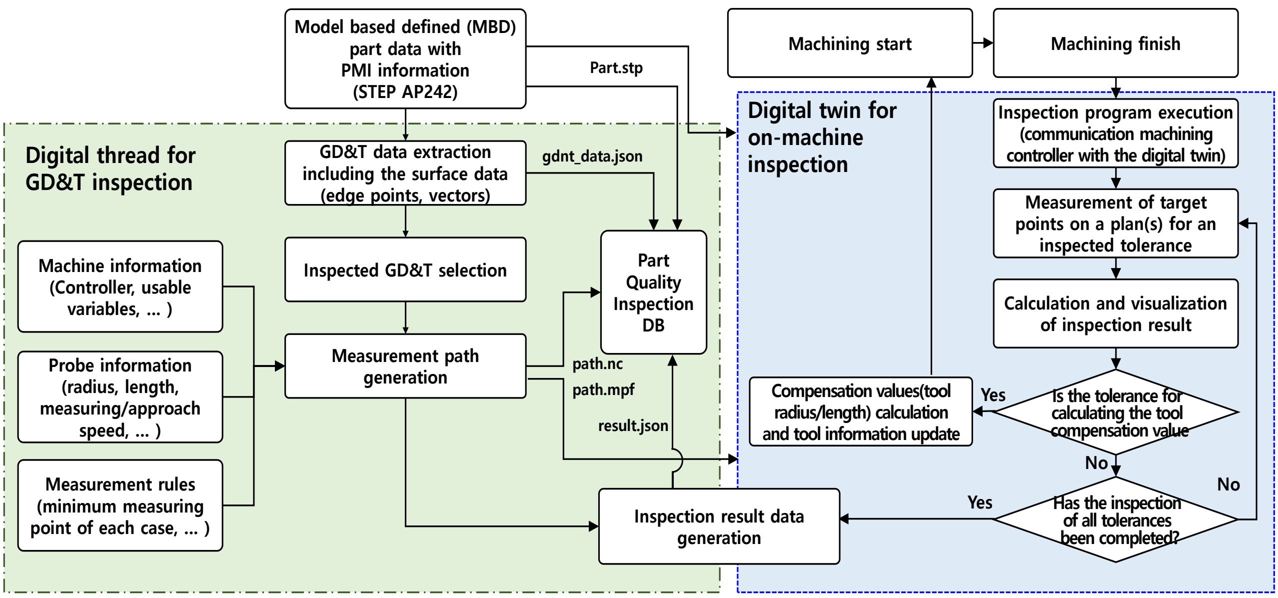

Figure 1. Procedure of the digital thread and the digital twin for the GD&T inspection via on-machine measurement

```
AP242_info" : {
    "gdt_data_ID" : "hmi_part_5_gdt_1",
    "rel_cad_data_ID" : "hmi_part_5_1",
    "update_date" : "2025-03-12 오전 10:53",
    "gdt_info" : {
        "num_gdt" : 3,
        "gdt_item" : [
            {
                "gdt_definition_entity" : "#14",
                "geometric_tolerance" : "DIMENSIONAL_LOCATION1",
                "description" : "linear distance",
                "magnitude" : " mm",
                "toleranced_geometry" : {
                    "shape_aspect" : "#424",
                    "advanced_face" : "#865",
                    "detailed_definition" : {
                        "gdt_type" : 16,
                        "normal_vector" : [ -1, 0, 0 ],
                        "sign" : -1,
                        "reference_vector" : [ 0, 0, 1 ],
                        "num_feature_point" : 4,
                            "point1" : [ 195, 113.439115247255, -30 ],
                            "point2" : [ 195, 124.358222275241, 3.5527136788005E-14 ],
                            "point3" : [ 195, 56.5608847527452, -30 ],
                            "point4" : [ 195, 45.6417777247591, 3.5527136788005E-14 ]
                    }
                },
                "toleranced_geometry2" : {
                    "shape_aspect" : "#423",
                    "advanced_face" : "#864",
                    "detailed_definition" : {
                        "gdt_type" : 16,
                        "normal_vector" : [ -1, 0, 0 ],
                        "sign" : 1,
                        "reference_vector" : [ 0, 0, 1 ],
                        "num_feature_point" : 4,
                            "point1" : [ 35, 45.6417777247591, 3.5527136788005E-14 ],
                            "point2" : [ 35, 56.5608847527452, -30 ],
                            "point3" : [ 35, 113.439115247255, -30 ],
                            "point4" : [ 35, 124.358222275241, 3.5527136788005E-14 ]
                    }
```


Figure 3. Extracted GD&T Data from STEP File of the example part model

3.2. Inspection path generation for the digital thread and the digital twin

The extracted GD&T data is utilized to generate probe measurement paths (inspection program) for quality inspection. The inspection program is automatically generated based on the tolerance requirements provided in the STEP file, and in cases of complex geometries, they can also be manually generated based on user judgment.

Measurement points are selected based on the `advanced_face` information within the GD&T data. The outer boundary of the surface is defined, and measurement points are distributed by applying an offset at specific intervals across the surface. Next, the geometric attributes of the surface plane and its normal vector are extracted. The relationship between thenormal vector and the reference vector obtained from the `advanced_face` data is analyzed to determine the surface orientation and the angles of the measurement points. Using the extracted normal and reference vectors, the probe's approach direction is established while evaluating potential collisions and kinematic constraints. Finally, the inspection path is optimized to minimize the probe's travel distance and maintain a consistent clearance between the probe and the surface.

The generated inspection path requires corresponding code generation, as the inspection results are analyzed and visualized using macro variables within the digital twin, which will be explained in Chapter 4. As shown in Figure 4, the inspection program is created by incorporating additional steps to store tolerance information and measurement values as macro variables. Macro variable #501 represents the start and end status of a single GD&T measurement and the overall inspection. Macro variable #502 represents the cumulative number of parts. Macro variable #503 indicates the type of tolerance, while #504 and #505 represent the tolerance range values (dimension/tolerance or +tolerance/-tolerance). Macro variable #507 records the number of user variables utilized. The target coordinates for the X, Y, and Z axes are stored in variables #508 to #510, whereas the measured coordinate values for the X, Y, and Z axes are stored in variables #511 to #513.

Table 1 Relationship between GD&T data and Inspection Path

GD&T data	Tool path
"geometric_tolerance" : "Dimemnsional_Location1"	("DIMENSIONAL_LOCATION1")
GD&T type : “Dimensional location”	#503=16
"magitude" : “160 (0.05) mm”	#504=160 #505=0.05
Total Number of measuring points	#506=8
Memory size of Macro Variables	#507=8+#506*6
"advanced_face" : "#864" "num_feature_point": "point3" “point3” : [35, 113.43911, -30] (Measurement point near point3)	(TARGET POINT Near point3 X=35.0000 Y=105.0000 Z=-10.0000)
	G90 G54 G01 X=#508-10.0000 Y=#509 Z =#510 F1000
X, Y, Z-coordinates of the measured point	#511~#513

```
("DIMENSIONAL_LOCATION1")
#501=0
#502=#502+1
#503=16
#504=160
#505=0.05
#506=8
#507=8+#506*6
(TARGET POINT X=35.0000 Y=105.0000 Z=-10.0000)
#508=35.0000
#509=105.0000
#510=-10.0000
G90 G54 G01 X=#508-10.0000 Y=#509 Z=#510 F1000
G31 G54 X=#508 Y=#509 z=#510 F400
#511=#5061-2.9842
#512=#5062
#513=#5063
G90 G54 G01 X=#508-10.0000 Y=#509 Z=#510 F1000
```

Figure 4. Generation of the quality inspection path for considering the GD&T information and measured point data in the digital twin


```
{
  "geometric_tolerance": "DIMENSIONAL_PLANE_TOLERANCE2",
  "num_gdt_points": 8,
  "gdt_point_measurement": [
    {
      "point_id": "p1",
      "X": "35.0230",
      "Y": "105.0000",
      "Z": "-10.0000"
    },
    {
      "point_id": "p2",
      "X": "35.0200",
      "Y": "105.0000",
      "Z": "-20.0000"
    },
    {
      "point_id": "p3",
      "X": "35.0250",
      "Y": "65.0000",
      "Z": "-20.0000"
    },
    {
      "point_id": "p4",
      "X": "35.0250",
      "Y": "65.0000",
      "Z": "-10.0000"
    },
    {
      "point_id": "p5",
      "X": "195.0830",
      "Y": "105.0000",
      "Z": "-10.0000"
    },
    {
      "point_id": "p6",
      "X": "195.0750",
      "Y": "105.0000",
      "Z": "-20.0000"
    },
    {
      "point_id": "p7",
      "X": "195.0790",
      "Y": "65.0000",
      "Z": "-20.0000"
    },
    {
      "point_id": "p8",
      "X": "195.0800",
      "Y": "65.0000",
      "Z": "-10.0000"
    }
  ],
  "gdt_result": 160.0186
},
```


Figure 5. Inspection result of the dimensional tolerance of the example part via the on-machine measurement

3.3. Measurement result data generation

Once the measurement of all tolerance inspection points is completed, the results of the GD&T inspection and coordinate data are stored in JSON format, as shown in Figure 5. The coordinate points of the reference plane (point_id P1–P4) and the measurement plane (point_id P5-P8) are presented. The generated GD&T measurement data consists of four components: `geometric_tolerance`, `num_gdt_points`, `gdt_point_measurement`, and `gdt_result`. The `geometric_tolerance` field specifies the type of tolerance being measured, while `num_gdt_points` indicates the total number of measured GD&T points. The `gdt_point_measurement` field contains the coordinate information of each measurement point in an array format, with each entry uniquely identified by a `point_id`. The X, Y, and Z coordinate values of each measurement point are stored, enabling verification of the geometric and dimensional quality of the inspected component. The `gdt_result` field represents the outcome of the inspection, providing an evaluation of whether the measured data meets the specified tolerance requirements.

4. Quality Inspection Digital Twin Model

4.1. Inspection digital twin with quasi-static synchronization

The on-machine inspection digital twin model is designed to synchronize the virtual physical model for quality inspection at certain intervals, as shown in Figure 6. The certain interval refers to the completion of each tolerance inspection. The synchronized measurement point data is processed to calculate the inspection results and present them within the specified tolerance limits. To achieve synchronization, communication between the digital twin model and the machining center controller is required. In this study, since a FANUC controller was used, FOCAS (FANUC Open CNC API Specifications) was utilized to access the macro variables of the machining center.

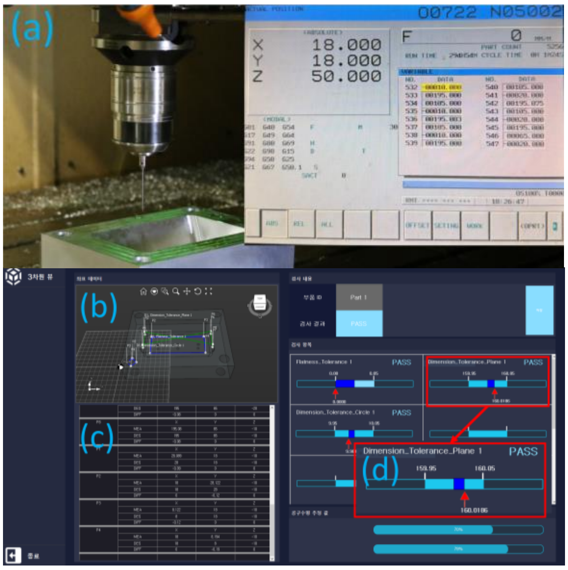

Figure 6. On-machine inspection and its digital twin model for the GD&T inspection of the example part (a) actual on-machine measurement (b) visualization of measured points, (c) measured point coordinates (raw data), (d) tolerance inspection results (closed up) calculated from raw data

4.2. Inspection result visualization

The inspection results are visualized, as shown in Figure 6, using the CAD model from the STEP file, the inspection path (program) provided by the digital thread, and the GD&T data. The digital twin also contains coordinate data, inspection details, inspection items, and tool life estimation values. The coordinate data includes both visual and numerical representations. The inspection details utilize a part ID to enable identification among identical parts and provide a comprehensive summary of the overall inspection results. The inspection items section provides detailed information on each inspection point, including tolerance values and the determination of whether the part meets the allowable tolerance.

The tool wear value is estimated from the dimensional tolerance inspection data and is calculated as the difference in dimensional errors by comparing it with the dimensional errors of the previous part. In this study, the digital twin model manages the tool wear limit based on a maximum wear threshold of 300μm, providing information on the appropriate timing for tool replacement.

4.3. Dimensional error estimation and compensation

The digital twin includes a function that estimates and compensates for diameter and length changes caused by tool wear based on dimensional tolerance inspection data. For parts that involve machining multiple components and require tool replacement, the tool information is updated and compensated through the digital twin model after machining one part and before machining the next. This approach can also be applied after rough machining, and it may be more effective if tolerances are set and measured on intermediate machined parts. The tool wear limit is determined by accumulating dimensional errors over time.

5. Conclusion

In this study, a STEP specification and on-machine inspection-based digital twin and digital thread model were proposed and implemented to ensure quality control and efficient management of machined components.

The Digital Thread provides systematic management of the quality inspection process by enabling GD&T data extraction, measurement path generation, and storage of inspection results in JSON format. By integrating data from each stage of manufacturing into the digital thread, the efficiency and reusability of data exchange across the design, manufacturing, and inspection stages are significantly enhanced. As a result, the entire machining and quality inspection process is operated in a data-driven manner, promoting the digitalization of quality management.

The Digital Twin facilitates quasi-static synchronization of measurement data during the quality inspection process, enabling real-time data acquisition and analysis during machining operations, thus providing immediate feedback. Furthermore, it enhances machining accuracy by estimating and compensating for dimensional errors caused by tool wear. The visualization of measurement results using GD&T data from STEP files provides users with an intuitive quality assessment environment, allowing for the rapid identification and resolution of quality issues.

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