Ontology Development for Knowledge Representation of a Metrology Lab

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ABSTRACT

Digital transformation in metrology is impacting the industry, where accurate and fair data are essential to take enterprises to the next level in the digital era. The amount and complexity of information are growing exponentially, and expert knowledge becomes imperative for users to perform measurement tasks and decision-making. This study presents the development of a modular metrological inspection ontology for a metrology laboratory based on the reuse of ontologies related to sensors and units of measurement. Such an ontology considers information about operators and customers (name, telephone number, email) and the linkage to service orders, pieces (length, height, width), measurement strategies (expert notes about measurement procedures and paths), and measuring machines (measuring scope, uncertainty, sensor probe). The proposed solution delivers a digitalized catalog that allows the user to filter records according to the geometrical characteristics of the pieces and recover notes related to measurement procedures and paths for similar cases. The purpose is to promote knowledge sharing and narrow the gap to achieve digital transformation toward Metrology 4.0 in laboratories prepared to offer metrological support.

Keywords-ontology; metrology; measurement strategy; CMM

I. INTRODUCTION

Metrology, standardization, accreditation, and conformity assessment are considered pillars of the quality infrastructure and have experienced significant changes in the digital era [1]. Metrology, as the science of measurement, is recognized as a core element in measurement processes related to international trade and exchange and deals with challenges and opportunities to achieve confidence and accuracy in the data [2]. In this regard, dimensional metrology refers to measuring geometric properties (i.e. length, area, and roundness) [3], supported by Coordinate Measuring Machines (CMMs) using geometrical and dimensional data obtained from Computer-Aided Design (CAD) models, commonly found in inspection planning systems [4-5]. A CMM measures the geometry of physical objects using discrete points distributed on the object's surface to assess product quality and control quality in manufacturing [6]. The digitalization of metrology is changing the way of working in industry by using new measurement techniques and fostering the adoption of information technologies to increase the efficiency of processes [7-8]. It enables adding information, such as product specification, with feedback during manufacturing workpieces [9-10], promoting the use of distributed measuring instruments and sensor networks from a holistic perspective [11]. Therefore, the digitalization of a measurement system includes four phases: definition of dimensional and geometric specifications, development of a measurement plan, measurement execution, and results [12]. Following this path, international initiatives such as the Inter-American Metrology project have task forces working on metrology for digital transformation toward Metrology 4.0 [13]. In this sense, ontologies facilitate the organization of knowledge and metadata from heterogeneous sources in a semantically significant, reusable, and interoperable way [14], supported by Semantic Web Technologies (SWT) [15]. Metadata and semantic relationships in a particular domain enable machines to infer new facts about the data and have a human-like understanding and reasoning [16-17]. To model and represent facts in the form of statements (subject, predicate, and object) and retrieve information, SWT employs standards and technologies such as the Resource Description Framework (RDF) [18], RDF Schema (RDFS) [19], Web ontology language (OWL) [20], and SPARQL protocol and RDF query language (SPARQL) [21-22]. Finally, logic reasoners (e.g. Pellet or Fact) infer logical consequences from ontologies through asserted facts or axioms [23].

Domain ontologies formalize the terms used in a discipline to enable separate systems to exchange information [24]. In the metrological domain, units of measurement are vital or critical in business for sales or purchases, construction of any machine or building, and anywhere a measure is needed [25]. The ontological modeling of metrological knowledge has been studied since the linked data emerged [26]. Examples are the Measurement Units Ontology (MUO) and the ontology of units of measure (OM2). Besides, the Quantities, Units, Dimensions, and Data Types (QUDT) ontology represents the vocabulary of unit standards to facilitate conversions and dimensional analysis [27]. Sensors used by machines or industry processes measure the performance or provide data for diagnoses. The W3C Semantic Sensor Network (SSN) group described an ontology for sensors in terms of capabilities, measurement processes, observations, and deployments [28-29]. In [30], it was used to contextualize measurements of metrological earth observations. In [31], the SSN ontology was extended for energy management to provide value-added services, and in [32], meteorological datasets were described.

Regarding the consumer knowledge domain, an ontology for designing products and services based on users was proposed in [33]. In [34], a semantic knowledge management system was developed to add value to customer experience. In [35], a decision support system was built using reasoning tools to enable manufacturing process selection and customer requirements. In [36], information on client loyalty, experience, and behavior was addressed, and in [37] an ontology was extended to support clients and track changes for social service provisioning. The motivation for the present work was twofold: the first was to develop a domain ontology in metrological inspection as a digitalized catalog for the Metrological Assistance Center of the University of Sonora as a support and decision-making tool for Metrology 4.0. The second was to count with a training tool for students and metrologists in formation interested in metrological aspects (e.g. the courses of measurement foundations and advanced metrology), providing a way to access expert knowledge.

II. MATERIALS AND METHODS

The Metrological Assistance Center of the University provides measurement and calibration services for different magnitudes to local manufacturing companies. One of the laboratories with the highest demand is coordinate metrology, which comprises the measured workpieces using CMM equipment, measurement reports, and data for calibration certificates. As shown in Figure 1, the laboratory has a FARO QUANTUM MAX articulated coordinate measuring arm with a range of 2 m and a precision of 0.003 mm, and a CMM Mitutoyo CRYSTA-PLUS 504 with a measuring scope: X-axis = 500 mm, Y-axis = 400 mm and Z-axis = 400 mm, with a resolution of 0.0005 mm (5 μm). It has a RENISHAW MH20i head adjustable on the A axis and rotates up to ± 180° in the X-Y plane. The B-axis rotates up to 90° in the Z plane.

Fig. 1. Equipment of the metrology lab: articulated arms and CMM unit.

The operative personnel using the equipment invest most of their time analyzing and designing measurement strategies (e.g. measurement order, probe selection) to generate reliable results, and they mostly use tacit knowledge in the metrology tasks, which are difficult to code and transfer. The client receives a measurement report of the workpiece, and a hard copy is filed. However, the knowledge used to perform the measurement tasks is not extracted and saved. This study aims to support the domain expert's knowledge extraction, employing an ontology to preserve it explicitly for the personnel or any interested user, providing measurement strategies (e.g. expert notes about measurement procedures and paths) to reuse these for future customers' needs. The Modular Ontology of Metrological Inspection (MOMI) was implemented using Protege software [38]. For its construction, the design took advantage of known methodologies [39-40]. It was essential to define and identify key concepts related to the workpiece, such as properties and characteristics to be sized (e.g. length, height, width, and metrological features), customer data (e.g. name, phone number, email), and CMM features (e.g. measuring scope, uncertainty). The Competency Questions (CQ) identified requirements, focused on fundamental concepts, and were formulated by experts and users in the metrology domain. A sample is presented as follows:

- CQ1: What is the customer's identification and service order assigned to a piece?
- CQ2: What are the geometric entities of a piece and coordinates?
- CQ3: What are the sensors used, dimensional and geometric tolerances, and tolerance limits of the geometric entity?

- CQ4: What is the piece name, serial number, and piece material?
- CQ5: What are the dimensions of the workpiece (length, width, and height)?
- CQ6: What is the measurement strategy applied?
- CQ7: What is the measurement scope of the CMM?
- CQ8: What is the resolution and uncertainty of the CMM?

In addition to the reused ontologies (SSN and QUDT), the proposed MOMI comprises two main modules: workpiece and customer. Figure 2 presents the workpiece module showing classes and subclasses for the piece data (e.g. name, material, serial number), and Figure 3 describes the faces of the workpiece with a maximum number of six faces, identified as faces A to F. According to the workpiece geometry to measure, each one of these classes could contain some geometric entities (lines or circles). As for the customer module, Figure 4 includes the subclasses that represent the contact data of the company representative, such as name, address, and email. Figure 5 illustrates an example of a workpiece to be measured with a pattern of four circles with a diameter of 12.500 ± 0.300 mm, and the center of the piece has a circle with a diameter of 22.200 ± 0.100 mm. Figure 6 shows an instance of MOMI with data on the Figure 5 workpiece and its relationships with the subclasses of customer, face, and geometric entities.

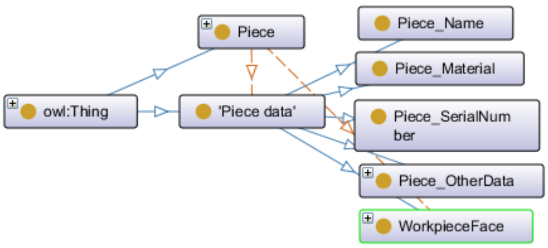


Fig. 2. The module of the workpiece: piece general data.

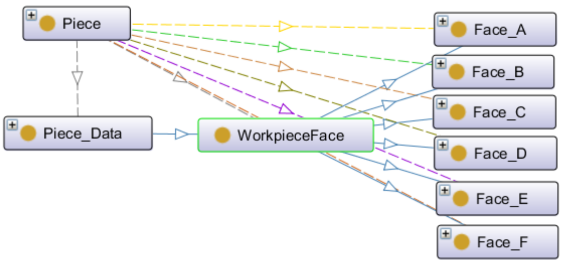


Fig. 3. The module of the workpiece: piece faces information.

III. RESULTS AND DISCUSSION

MOMI was verified with the Pellet reasoning plugin, returning a consistent ontology model and SPARQL to answer the CQs. Figure 7 shows the results for CQ1 to CQ3, where the columns service order, customer, and piece link the customer with the workpiece to be measured. The column *observGeom* refers to the observed geometric entities. For instance, Piece_P001 has five circle entities. The following columns show the diameter, sensor, 3D coordinates, dimension tolerances (positive and negative values), and geometric tolerance. Thus, the second row indicates a diameter of 22.189 mm and a geometric tolerance (*geoTolValue*) of 0.2 mm.

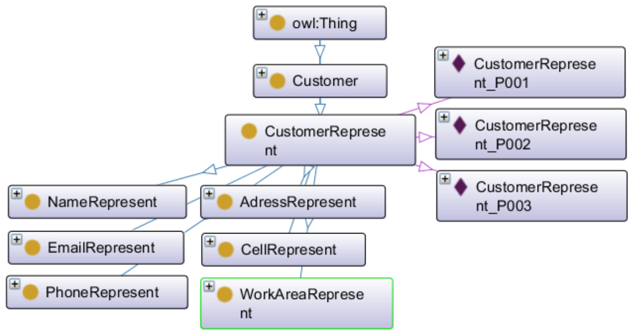


Fig. 4. The module of customer data.

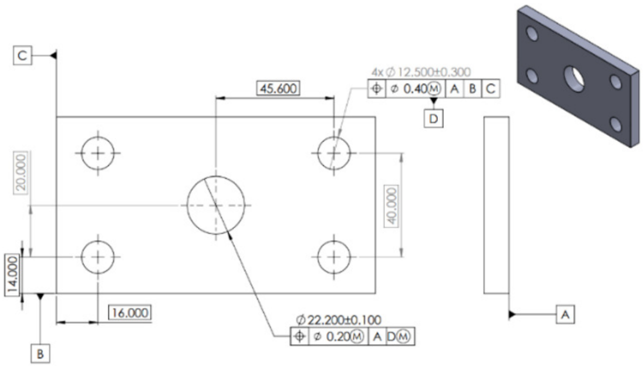


Fig. 5. Technical drawing of a workpiece to be measured.

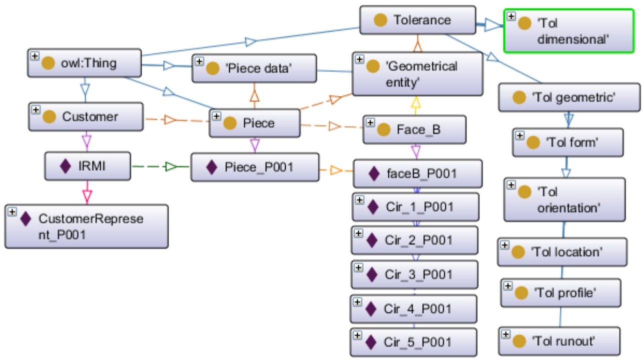
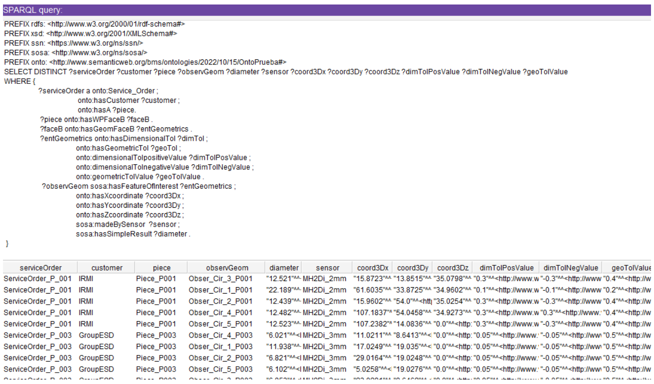


Fig. 6. A partial view of the classes of the modular ontology of metrological inspection.

Figure 8 illustrates a complex piece to measure with the CMM, labeled with points A and B for context in the implemented measurement strategy. Figure 9 shows the SPARQL query to answer CQ4 to CQ6 based on the data captured from the workpiece. The columns show the values for the piece, piece name, serial number, material, length, width, height, and strategy. The bottom of Figure 9 partially describes the measurement strategy. Such a strategy comprises the steps to capture the measurement plan of the piece and facilitate the future measurement process of similar workpieces. The next step is to populate the ontology with historical records of the Metrological Assistance Center of the University from the last couple of years and create electronic records with relevant information, specifically to recover the different measurement strategies.



SPARQL query:

```
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX ssn: <https://www.w3.org/ns/ssn/>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
PREFIX onto: <http://www.semanticweb.org/bms/ontologies/2022/10/15/OntoPrueba#>
SELECT DISTINCT ?serviceOrder ?customer ?piece ?observGeom ?diameter ?sensor ?coord3Dx ?coord3Dy ?coord3Dz ?dimTolPosValue ?dimTolNegValue ?geoTolValue
WHERE {
        ?serviceOrder a onto:Service_Order ;
                onto:hasCustomer ?customer ;
                onto:hasA ?piece.
        ?piece onto:hasWPFaceB ?faceB .
        ?faceB onto:hasGeomFaceB ?entGeometrics .
        ?entGeometrics onto:hasDimensionalTol ?dimTol ;
                onto:hasGeometricTol ?geoTol ;
                onto:dimensionalTolpositiveValue ?dimTolPosValue ;
                onto:dimensionalTolnegativeValue ?dimTolNegValue ;
                onto:geometricTolValue ?geoTolValue .
        ?observGeom sosa:hasFeatureOfInterest ?entGeometrics ;
                onto:hasXcoordinate ?coord3Dx ;
                onto:hasYcoordinate ?coord3Dy ;
                onto:hasZcoordinate ?coord3Dz ;
                sosa:madeBySensor ?sensor ;
                sosa:hasSimpleResult ?diameter .
}
```

serviceOrder	customer	piece	observGeom	diameter	sensor	coord3Dx	coord3Dy	coord3Dz	dimTolPosValue	dimTolNegValue	geoTolValue
ServiceOrder_P_001	IRMI	Piece_P001	Obser_Cir_3_P001	"12.521"^^	MH2Di_2mm	"15.8723"^^	"13.8515"^^	"35.0798"^^	"0.3"^^<http://www.w	"-0.3"^^<http://www	"0.4"^^<http://w
ServiceOrder_P_001	IRMI	Piece_P001	Obser_Cir_1_P001	"22.189"^^	MH2Di_2mm	"61.6035"^^	"33.8725"^^	"34.9602"^^	"0.1"^^<http://www.w	"-0.1"^^<http://www	"0.2"^^<http://w
ServiceOrder_P_001	IRMI	Piece_P001	Obser_Cir_2_P001	"12.439"^^	MH2Di_2mm	"15.9602"^^	"54.0"^^<htt	"35.0254"^^	"0.3"^^<http://www.w	"-0.3"^^<http://www	"0.4"^^<http://w
ServiceOrder_P_001	IRMI	Piece_P001	Obser_Cir_4_P001	"12.482"^^	MH2Di_2mm	"107.1837"^	"54.0458"^^	"34.9273"^^	"0.3"^^<http://www.w	"0.3"^^<http://www.	"0.4"^^<http://w
ServiceOrder_P_001	IRMI	Piece_P001	Obser_Cir_5_P001	"12.523"^^	MH2Di_2mm	"107.2382"^	"14.0836"^^	"0.0"^^<http:	"0.3"^^<http://www.w	"-0.3"^^<http://www	"0.4"^^<http://w
ServiceOrder_P_003	GroupESD	Piece_P003	Obser_Cir_4_P003	"6.021"^^<	MH2Di_3mm	"11.0211"^^	"8.6413"^^<	"0.0"^^<http:	"0.05"^^<http://www.	"-0.05"^^<http://ww	"0.5"^^<http://w
ServiceOrder_P_003	GroupESD	Piece_P003	Obser_Cir_1_P003	"11.938"^^	MH2Di_3mm	"17.0249"^^	"19.035"^^<	"0.0"^^<http:	"0.05"^^<http://www.	"-0.05"^^<http://ww	"0.5"^^<http://w
ServiceOrder_P_003	GroupESD	Piece_P003	Obser_Cir_2_P003	"6.821"^^<	MH2Di_3mm	"29.0164"^^	"19.0248"^^	"0.0"^^<http:	"0.05"^^<http://www.	"-0.05"^^<http://ww	"0.5"^^<http://w
ServiceOrder_P_003	GroupESD	Piece_P003	Obser_Cir_5_P003	"6.102"^^<	MH2Di_3mm	"5.0258"^^<	"19.0276"^^	"0.0"^^<http:	"0.05"^^<http://www.	"-0.05"^^<http://ww	"0.5"^^<http://w

Fig. 7. Customer service orders and measured piece data.

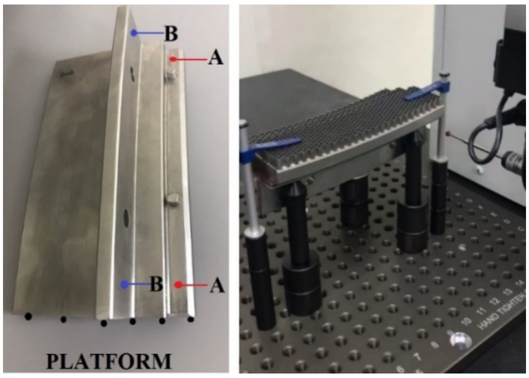
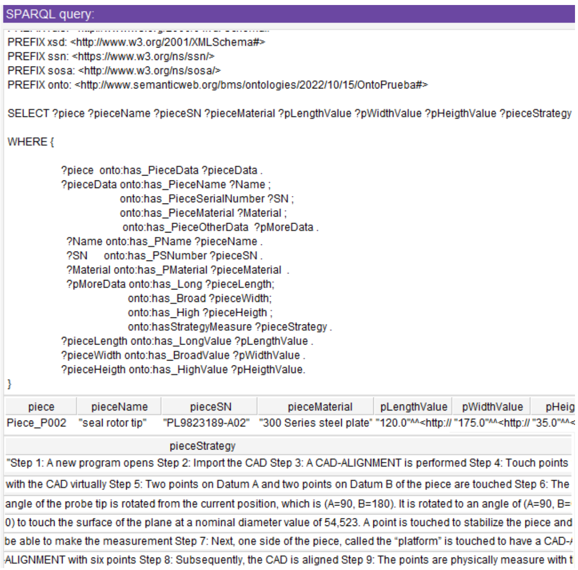


Fig. 8. A seal rotor tip workpiece measured by a CMM.



SPARQL query:

```
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX ssn: <https://www.w3.org/ns/ssn/>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
PREFIX onto: <http://www.semanticweb.org/bms/ontologies/2022/10/15/OntoPrueba#>

SELECT ?piece ?pieceName ?pieceSN ?pieceMaterial ?pLengthValue ?pWidthValue ?pHeigthValue ?pieceStrategy

WHERE {

        ?piece  onto:has_PieceData ?pieceData .
        ?pieceData onto:has_PieceName ?Name ;
                onto:has_PieceSerialNumber ?SN ;
                onto:has_PieceMaterial ?Material ;
                onto:has_PieceOtherData  ?pMoreData .
        ?Name onto:has_PName ?pieceName .
        ?SN     onto:has_PSNumber ?pieceSN .
        ?Material onto:has_PMaterial ?pieceMaterial  .
        ?pMoreData onto:has_Long ?pieceLength;
                onto:has_Broad ?pieceWidth;
                onto:has_High ?pieceHeigth ;
                onto:hasStrategyMeasure ?pieceStrategy .
        ?pieceLength onto:has_LongValue ?pLengthValue .
        ?pieceWidth onto:has_BroadValue ?pWidthValue .
        ?pieceHeigth onto:has_HighValue ?pHeigthValue.
}
```

piece	pieceName	pieceSN	pieceMaterial	pLengthValue	pWidthValue	pHeig
Piece_P002	"seal rotor tip"	"PL9823189-A02"	"300 Series steel plate"	"120.0"^^<http://	"175.0"^^<http://	"35.0"^^<

pieceStrategy
"Step 1: A new program opens Step 2: Import the CAD Step 3: A CAD-ALIGNMENT is performed Step 4: Touch points
with the CAD virtually Step 5: Two points on Datum A and two points on Datum B of the piece are touched Step 6: The
angle of the probe tip is rotated from the current position, which is (A=90, B=180). It is rotated to an angle of (A=90, B=
0) to touch the surface of the plane at a nominal diameter value of 54,523. A point is touched to stabilize the piece and
be able to make the measurement Step 7: Next, one side of the piece, called the "platform" is touched to have a CAD-/
ALIGNMENT with six points Step 8: Subsequently, the CAD is aligned Step 9: The points are physically measure with t

Fig. 9. A query to recover information on the seal rotor tip with the measurement strategy employed.

The digital transformation applied in the metrology field fosters the adoption of information technologies [41]. It supports the integration of sensor measurements to assess product and control quality [42], along with path planning for automated inspections [43]. In this sense, ontologies enable the knowledge representation of industries and measuring processes in quality inspection and control [44]. In [45], an intelligent inspection model of prismatic parts was presented to support the definition of metrological sequences and the planning of measuring probe paths. In addition, in [46], a framework with the onto-process ontology was proposed to automate inspection planning strategies that convert implicit knowledge into explicit knowledge to implement a knowledge-based application. Furthermore, in [47] a digital twin framework was introduced to exhibit components and data flow for the assembly part process. This study considered assembly constraint relationships and filter key assembly features for processing and inspection. Likewise, in [48], the measurement process and information on uncertainty were addressed using logic reasoners, enabling semantic modeling, automated analysis, and discovery of traceable measurement data. In this vein, in [49], an inspection planning system was created to optimize the measurement path for metrology using artificial intelligence techniques (e.g. ontology, genetic algorithms, and ant colony optimization). Table I shows the employed criteria for identifying similarities between the above studies and the proposed one.

The main criteria considered in this study were modeling, methodology, geometric dimensioning and tolerances, and users. OWL was adopted to create the ontology in most works and UML to support the modeling. Additionally, the preferred methodology was ontology development 101.

TABLE I. COMPARISON BETWEEN MOMI AND RELATED WORKS

Criteria	[45]	[46]	[47]	[48]	[49]	MOMI
Modeling	owl	uml	owl; uml	owl; uml	owl	owl
Methodology	o1	oo	o1	o1; oo	o1	o1; mom
Reuse ontology	yes	yes	no	no	yes	yes
Evaluation [50]	-	-	-	ir; q	ir	q
Geometric dimensioning and tolerances	yes	yes	yes	yes	yes	yes
Users	-	op	op	op	-	cu; op
Implementation	no	c++	sql; -	no	m; p; s	no

Modeling: owl=web ontology language, uml=unified modeling language. **Methodology**: mom=modular ontological modeling, o1=ontology development 101, oo=object oriented. **Evaluation:** q=competency questions, ir= inference rules. **Users**: cu=customer, op=operator. **Implementation**: m=MatLab, p=ptc, s=step-nc, sql=MySql. **"-"**=not mentioned.

Regarding the reuse of ontologies, most studies used or extended a previous ontology, and a couple built their ontology from scratch [47-48]. On the contrary, this study reused SSN and QUDT ontologies. Most of the reviewed research works, including MOMI, applied the ontologies in the context of CMM equipment, except in [45], which also considered different kinds of machining equipment and MOMI to address articulated arms.

The knowledge of the current state of the development of ontologies related to computer science and engineering areas in

México motivated us to conduct a study to identify the characteristics of the creation, extension, and use of ontologies. This ongoing research reveals that even though the fields of manufacturing and industry are addressed, research studies on ontologies related to the metrology inspection of workpieces were not found in the analyzed time frame (1999-2022).

MOMI is based on well-known concepts related to sensors, quantities, and units from previous ontologies employed in the metrological area. Furthermore, the ontology classes related to geometrical dimensioning and tolerances, such as location tolerance (Q109523965), orientation tolerance (Q109483186), and runout tolerance (Q109523972) were developed and registered in Wikidata [51]. The proposed work considered information about operators and customers, linking them to service orders, pieces, and measurement strategies by providing a digitalized catalog and a training tool to promote knowledge sharing and narrow the gap to achieve digital transformation toward Metrology 4.0.

IV. CONCLUSIONS

This study proposes a modular metrological inspection ontology for a metrology laboratory to provide access to expert knowledge in the measurement field. It preserves such knowledge explicitly for the operative personnel or any interested user by filtering records according to the geometrical characteristics of pieces and recovering notes related to measurement procedures and paths for similar cases (e.g, the measured seal rotor tip workpiece). The ontology can serve as a digitalized catalog for measured workpieces, reports, and data for calibration certificates. In the same vein, the proposal's strength is based on the reuse of well-known ontologies (SSN and QUDT) to model concepts of the metrological field and the linkage of the information about operators and customers concerning service orders, measured pieces, and measurement strategies to support the digital transformation toward Metrology 4.0. Future work directions would embrace the development of a system that incorporates the modular inspection ontology to provide adaptive and personalized strategies and facilitate the measurement of workpieces.

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