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ONTOLOGICAL MODEL CENTERED ON RESOURCE CAPABILITIES FOR THE INSPECTION PROCESS PLANNING

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Abstract

Planning of a manufacturing process is a knowledge-intensive task in which a lot of information/knowledge must be managed, especially to the most conceptual levels. One of these tasks that is realized at supervisor planning level, consists of the assignment and configuration of resources for each activity to execute. Decisions that must be based on the resource capabilities, which depend largely on resource configuration, so that they can ensure a good result. As it is well known, the ontological approaches have shown well positioned in these cases where knowledge management is needed, moreover, these approaches enable a shared conceptualization, which make it possible to implement process planning in a collaborative environment, particularly when they are accompained by a methodology that facilitates their interpretation and use.

In previous researches, a general ontology for modelling the resource capabilities involved in a process has been proposed. This ontology has been specialized in order to support the process planning task and a methodology supported on graphical representation for validating the configurations of resources assigned in a manufacturing process has been proposed. Based on these results, in this paper, an extended ontology for the inspection process planning is presented. This extension includes new types of activities (inspection activities) and new type of resources (inspection resources), and is centered on the dimensional and geometrical capabilities of the resources. Additionally, using the ontology semantics and the proposed methodology, an application for an inspection plan is developed. The inspection process planning case is focused on the preparation activities used for obtaining the configurations of the resources, since they largely determine the capabilities of the resulting resources. The application demonstrates the proficiency of the ontology to execute manufacturing planning and inspection planning in a dual form.

Keywords: Inspection process planning, resource capabilities, ontological modelling.

1. Introduction

Planning of a process is a knowledge-intensive task that determines the activities to be performed, the order of execution or sequence and the resources to use in order to obtain the desired results (such as the machining plan of a workpiece, the inspection plan of a workpiece, or the development plan itself of a product or process) according to imposed requirements. It is an activity that is particularly relevant in manufacturing process and especially in machining and inspection process subdomains, which have been studied both individually and jointly (Kramer et al., 2001; Rosado et al., 2009).

In machining processes, process planning establishes the set of manufacturing operations, their sequence and manufacturing resources necessary to obtain a part with dimensional and geometric characteristics that determine its quality. These dimensional and geometric characteristics of the manufactured parts (qualities) depends largely on all decisions taken during planning and especially the decisions concerning the selection and configuration of individual resources to be used in the implementation of each operation. Decisions that must be based on the resource characteristics (capabilities) so that they can ensure a good result. Moreover, quality of the products and the manufacturing process itself is controlled by means of inspection processes, which aims to measure the quality characteristics of the manufactured parts or the manufacturing process to make the adjustments needed. An inspection process that must ensure that the measurement of the characteristics is performed with proper uncertainty because otherwise the values obtained will not be representative. The type of characteristics to control and their uncertainty depends largely on decisions made during the inspection planning and especially on the selected resources. Improper selection of resources can completely invalidate the results obtained with a particular inspection plan.

Moreover currently, to exploit the benefits of an integrated and collaborative product development is necessary to consider an integrated manufacturing and inspection process planning. In last generation manufacturing systems, the inspection and manufacturing operations to be carried out are sequenced together, allowing leverage the capabilities that have the resources to execute manufacturing and inspection operations, and empowering, as mentioned, effective interaction between manufacturing process and the results. This is particularly relevant in cases where inspection online or in-process is realized (Bruscas, 2015).

But for the development of integrated planning task of manufacturing and inspection, the planner needs to manage a lot of information and knowledge, as well as an integrated perspective of manufacturing and inspection processes. The ontological approaches have shown well positioned in these cases where knowledge management and the use of a shared conceptualization between the actors involved are important aspects (Solano, 2015). Therefore, it is necessary to develop models of information / knowledge capable of capturing useful knowledge for planning, designed to ensure the validity of decisions taken with respect to resources.

Perhaps, the most noteworthy contributions in modeling information of the resource capabilities that have been put forward are those included in MANDATE (ISO, 2004-1), which presents an integrated model for the management of manufacturing resources. Others non-standardized contributions are the ones of Newman and Nassehi (2009), that proposes the concept of resource capability profile defined as an aggregation of the individual profiles, and Ameri and Dutta (2008) and Cai et al. (2011) centered in modeling manufacturing resources and services in e-manufacturing and collaborative supply chains domains. Otherwise in Solano et al. (2014) and Solano et al. (2016) PPDRC (Product and Processes Development Resource Capability) ontology and MIRC (Manufacturing and Inspection Resource Capability) ontology are proposed respectively.

PPDRC ontology is more general and was designed for supporting development of product and processes in collaborative environments, including the integrated process planning. It incorporates concepts from DOLCE (Oberle et al., 2007), PSL (ISO, 2004-2) and MANDATE. DOLCE provides to PPDRC the concepts necessary to represent the social and agentive character of the resources, a fundamental aspect in collaborative processes. By other hand, the concepts about activities and their execution are derived from PSL ontology, which possesses sufficient semantic richness to support any planning and execution activity. Each activity execution requires the intervention of any type of resource. In fact, one of the fundamental tasks in process planning is the definition, configuration and assignment of resources to use in the execution of an activity. Nevertheless, the description and structuring of resources is not taken into account in PSL. The fundamentals of resource conceptualization of PPDRC are derived from MANDATE, including the resource capability and capacity concepts. The capability of a resource characterizes its participation in a type of activity, expressing the skills required to execute activities of that type and, should it be the case, the level of performance reached in executing them. A capacity, however, is a type of capability expressed in terms of amount of production (like inspection rate or inspection speed).

The aforementioned MIRC ontology is a specialization of PPDRC ontology. It provides a valid integrated process (manufacturing and inspection) planning conceptualization framework and supports integrated machining and inspection process planning in collaborative environments. MIRC ontology supports the knowledge needed to make decisions about the tasks involving: (a) configuration and assignment of machining and inspection resources, and (b) evaluation and validation of integrated machining and inspection process plans, carried out at supervisor level. In this context, resource configuration is understood as referring to all the activities aimed towards defining a complex resource, starting out from the elemental resources that it is made up of, and determining the technological capabilities related to the definition of necessary preparation activities (loading and setup), their sequence and the resources used to perform them. Although MIRC ontology may support other characteristics (qualities), it focuses especially on dimensional and geometric characteristics and their variabilities. This makes it possible to determine the type of evaluation techniques that can be used.

PPDRC and MIRC have been implemented in OWL (Jang et al., 2008) using Protégé (Gennari et al., 2003) as ontology editor. OWL allows the definition of ontologies based on first-order logic. Additionally, to overcome OWL limitations and to allow the realization of classification and reasoning processes (inference) in the ontology, reasoner Pellet (Pellet OWL2 API) was used. Furthermore, to allow consultations and interaction with the user, an application that uses the query language SPARQL (Mariot et al., 2007) has been developed.

Another result of work carried out in recent years by the research teams of Polytechnic University of Valencia and University Jaume I of Castellón has been the proposal of a methodology that helps the planner in the validation task of manufacturing plans (Solano et al., 2015). The methodology, supported by MIRC ontology, is based on a set of graphic representations that allow visualization of the composition and quantification of the characteristics associated to the resources and objects involved in the execution of the different activities by linking them with the characteristics of the objects or resources resulting from these activities.

In this paper, and in order to highlight the validity of the MIRC ontological proposal for integrated process planning, it will be exposed a specialization of MIRC taxonomy for the task of planning an inspection process at the supervisor level. But before showing the specialization of the ontological model, in the next section a brief review of MIRC ontology entities and predicates is done, and then MIRC taxonomy is extended incorporating entities for inspection processes. In next section, a graphical representation for the activities of a inspection process plan enabling analysis to validate the adequacy of selected resources will be exposed. Finally, as a case study, the development of an inspection plan is described, emphasizing its parallelism with manufacturing plan development and paying particular attention to resource selection and validation tasks.

2. Specialization of MIRC ontology for inspection activities

2.1. Concepts and entities in MIRC ontology

The MIRC ontology is a specialization of PPDRC ontology, which essentially uses concepts from DOLCE, PSL and MANDATE, as previously indicated. The social object concept, taken from DOLCE, is very important in the PPDRC ontology. The social objects are used to describe shared concepts such as: activities, resources, capabilities, etc. that are necessary to stablish and manage a process plan.

The first level entities and relations in the MIRC ontology are shown in Figure 1. *Activities* are the basic entities that make up the process plan and, when carried out (*ActivityOccurrences*) they represent the execution of the plan. The entity *ActivityType* represents the types to which *Activities* belong. Every time a working part of the batch is inspected an *ActivityOccurrence* is being carried out. *Object* is a tangible or intangible entity with existence, as the persons and instruments used in inspection activities or the inspection results. *Characteristic* is an entity whose individuals express the qualities of other individuals of the ontology. They are quantified by *Regions*. Any object can have a relationship with the type *Characteristic* via the predicate *characterizedBy* (*Object*, *Characterisitic*), while the predicate *parametrizes* (*Characteristic*, *Region*) expresses the relationship existing between a characteristic and the regions that quantify it. *Resources* are objects which have the competence or ability (capability) to carry out an activity, and reach a determined level of performance in this execution. *Roles* are the description of how a physical object participates in the execution of an activity (*ActivityOccurrence*), and may belong to the following types: *Mechanism*, *Input*, *Output* and *Control*. Objects with a mechanism role are those executing the activity. The rest of the objects that take part in an *ActivityOccurrence* act as: *Input*, the object that is transformed in the activity; *Control*, the object that specifies the execution conditions required to produce the desired results; or *Output*, the object resulting from the execution of the activity.

The entity *Capability* is a specialization of *Characteristic* which characterizes the use of a resource executing a particular type of activity. A capability is the ability or possibility of carrying out a type of activity with a level of performance quantifiable via regions. The relationship that exists between a capability and its regions is expressed through the predicate *parametrizes* (*Capability*, *Region*), which has two specializations: *parametrizes_Occ*, which relates regions quantifying activity execution and *parametrizes_Object*, which relates regions quantifying characteristics transmitted to output object. To consider the influence of the characteristics of the input object on which the activity is being executed, the ontology uses the predicate *requires* (*Capability*, *Region*), which expresses the requirements demanded of the characteristics of the object on which the activity is being carried out in relation to the resource's capability to execute activities of this type.

In general, the changes that are produced in a physical object when an activity is executed are shown by the regions of its characteristics. In the case of manufacturing activities, these changes are reflected in the physical characteristics of the object. However, on occasions, the modification to the capabilities of a resource may be due to logical changes, changes in data or changes to location of the resource, as in inspection activities, where only the characteristics of the social object linked to the part that has been inspected are modified. These objects (or resources) modifications that are not accompanied by physical changes lead to versions of the object (or resource) which are related through the transitive predicate *hasVersion* (*Object*, *Object*). Thus, the predicate *hasVersion* allows to maintain different versions of an object, which is involved in the inspection process, depending on the calibration status, conditions of use, historical information, data catalog, etc.

The predicate *formedBy* (*Object*, *Object*) enables the representation of object which in turn is made of other objects. For example, it allows the representation of complex resources which are formed by other resources. When physical connections are established between the elemental resources that make up a complex resource, each of these connections or links carries with it a feature of the interface type. The predicate *relatedTo* (*Object*, *Object*) establishes the relationships that exist between physical resources that are connected by interfaces. Thus, this predicate gives more information on resources that make up a complex resource than that given by the predicate *integratedBy* (especialization of *formedBy*).

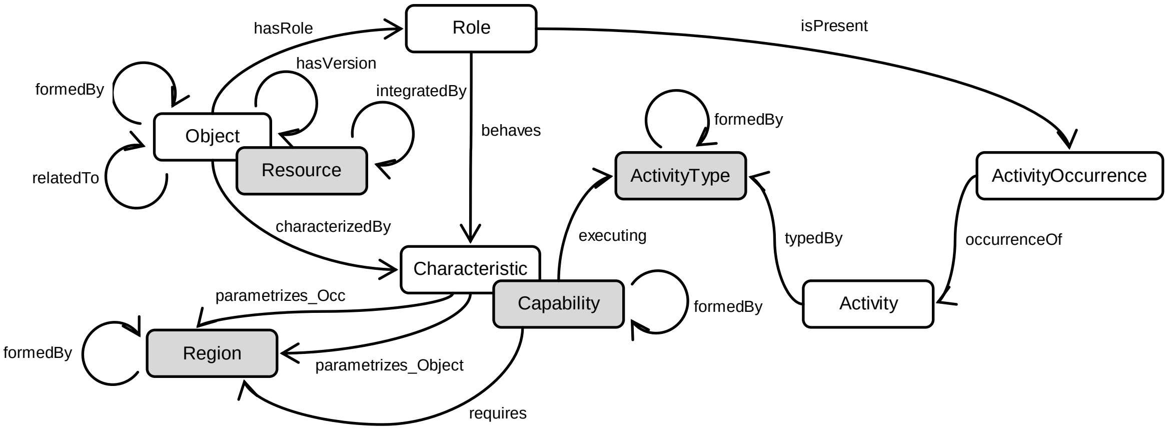

Figure 1. Predicates of the MIRC ontology

2.2. MIRC extension for inspection

MIRC ontology that shares the general concepts of the PPDRC ontology, can tailor inspection resource activities and capabilities with the aim of supporting all the knowledge necessary to carry out all decision making – linked to the selection, assignment and preparation of resources – that takes place during the inspection process planning. For this, specialization of the entity *Capability* is required, along with the regions which quantify it, and specializations of the entities *ActivityType* and *Resource* (Figure 2), which are necessary to define and understand the capabilities.

MIRC ontology was described focusing basically on entities that support manufacturing activities. Figure 2 shows a part of MIRC taxonomy, which although not complete puts the focus on the entities that are specializations of the *ActivityType* and *Resource* classes to support the inspection planning. See (Solano et al., 2016) for a more complete description of MIRC ontology. This allows showing the uniformity of treatment given to manufacturing and inspection, and therefore the validity for an integrated manufacturing and inspection process planning. The figure shows the capabilities that are directly related to the inspection process. Specifically, it shows the regions of variability type in MIRC ontology that are of interest for inspection of dimensional and geometric specifications: *Dimensional_Variability* (DV) expressing variability in lengths and angles, *Own_Geometric_Variability* (OGV) expressing intrinsic geometric variability and *Reference_Geometric_Variability* (RGV) expressing variability in orientation and position among geometric elements.

The inspection process plan can be seen as a collection of planned activities to be executed with resources that have a mechanism role, with the purpose of quantify the characteristics values of a part feature that has been previously produced by a manufacturing process. Among the various activities that make up the inspection plan, it can find ones for creating or modifying the characteristics of the resources that participate in the activity of the inspection plan and others for obtaining information on the physical characteristics of the part. Some activity types in the MIRC ontology have been specialized to incorporate the activity types for inspection. Specifically, it has been defined the activity type *Qualification,* a specialization of *Setup* activity type which is used in the preparation of a resource for inspection and the activity type *Inspection,* a specialization of *Operation* activity type which defines an inspection operation. An *Inspection* activity type is a concurrent grouping of activities of types *Tool_Part_Interaction* and *Tool_Movement*, where *Tool_Part_Interaction* represents the interaction between the tool and the part to be processed (the probe and the part to be inspected), and *Tool_Movement* represents the relative movement between the probe and the part. A *Tool_Movement* is the combination of movements (linear or rotatory) which are defined by the inspection operation strategies. In turn, the individuals of the type *Tool_Part_Interaction* can be of two types: *Contact* and *No_Contact*, depending on the characteristics of the interface between probe and part. Inspection operations have been specialized in: (a) *Dimensional*, corresponding to the inspection of a length or angle; (b) *Own_Geometry* (OG), corresponding to the inspection of a form characteristic such as flatness, circularity, etc.; and (c) *Relation_Geometry* (RG), corresponding to the inspection of a relative situation characteristic such as parallelism, perpendicularity, etc.

Finally, it should be noted that MIRC classes corresponding to the resources have been also specialized incorporating those resources that have capabilities to execute activities of type *Inspection*. In this sense, the *Resource_Element* has been specialized incorporating the *Stylus*, *Probe* and *Extension* (Extension Bar) classes, which are resources with capability to execute *Tool_Part_Interaction* activity types, and *Coordinate_Measuring_Machine* (CMM) and *Roundness_Machine* classes, among others, which are resources with capabilities to execute *Tool_Movement* activity type. It has also been specialized the *Resource_Group* incorporating the *Inspection_Resource* class, which represents all those resources with capability to execute *Inspection* activity type, and the classes *Motorised Probe Head* (MPH) and *Touch_Trigger_Probe* (TTP), which represents a *Resource_Group* formed by a *Stylus* and a *Probe*.

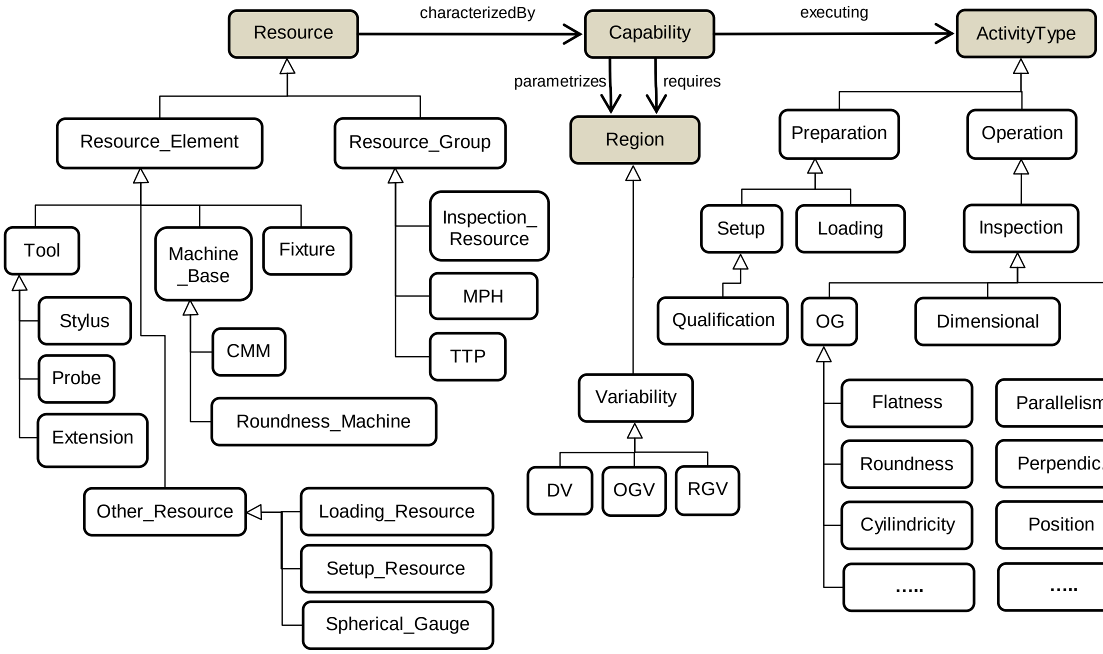

Figure 2. Taxonomy of the entities *Resource*, *Region* and *ActivityType* in the MIRC ontology

3. Graphical representation of inspection activities

In (Solano et al., 2015) it was shown a graphical representation for manufacturing activities that gives support to the methodology for the validation of resource selection in process planning. This graphical representation, that will now be applied to activities that form an inspection plan, facilitates quantification of the characteristics obtained, is based on the concepts of MIRC ontology and the graphs used can be constructed from the ontology individuals and their relationships. Figure 3 shows the graphical representation of an activity, where the activity execution is represented by the vertical axis, and characteristics of the objects that take part in this execution with *Input*, *Output*, *Mechanism* and *Control* roles, are represented by the dotted line, double solid line, solid line and solid/dotted line respectively that are joined to the activity interface (hinge). The figure emphasizes the fact that object characteristics with *Input* and *Mechanism* roles are the result of the execution of previous activities, forming a chain of activities that represents the inspection plan.

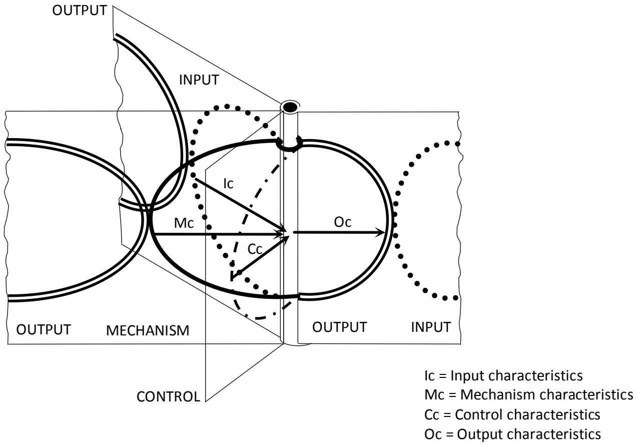

Figure 3. Spatial representation of the chain of characteristics associated to the execution of an activity

A plane representation of the activity execution, arising from the abatement of a combination of Input (I), Mechanism (M), Control (C) and Output (O) plans of the spatial representation, is shown in Figure 4. This view allows to appreciate the approach that ontology adopts for obtaining (composing) the characteristics of the output object of execution activity. The following principles have been adopted: (a) the characteristics of the output object are obtained through the composition of the resource capabilities and interface characteristics (represented by the broken line) forming a chain of characteristics; (b) the capabilities of a resource are conditioned by the fulfillment of certain characteristics of the input object; and (c) the characteristics of the interface are regulated by the characteristics that control the activity. The characteristics of the interface are established between the active geometries during the activity.

While in the machining activities, new features with their tolerances are embodied in the output objects, in the inspection activities, the result will be the measured characteristics of the features of the output objects with the associated uncertainties (variability limits). These uncertainties of the measured characteristics that depend on the resources used in the execution of the activity and on the activity execution itself must be compatible with tolerances of the characteristics to inspect.

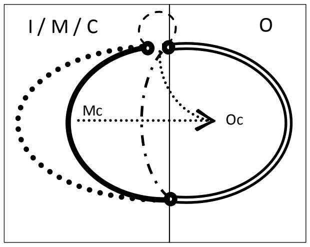

Figure 4. Plane representation of an activity execution

The representation of an inspection activity in a planar graph (Figure 4) shows that its execution always results in at least one characteristic of the output object, which is the result of a unique resource intervention that works with the mecanism role. However, this resource can be simple, consisting of a single element or compound formed by the grouping of several resources as a result of previous preparation activities (Figure 7). Sometimes the object characteristic to be inspected is not obtained directly from an inspection activity, but is the result of the composition of two or more characteristics obtained in different activities. These characteristics, which are obtained indirectly, are represented by an arc line of three lines between the characteristics that are composed. In these situations, the resources that act with the role of mechanism for obtaining the composed characteristics may be different, but the reference of these features must be the same. This coincidence in the reference is shown with a thick dashed line (Figure 5), linking this common reference. Figure 5(a) shows an indirect obtaining feature (*Char_A-B*) from two features (*Char_A* and *Char_B*) obtained with the same resource. In Figure 5(b), the same situation is shown when the two characteristics are obtained with different resources.

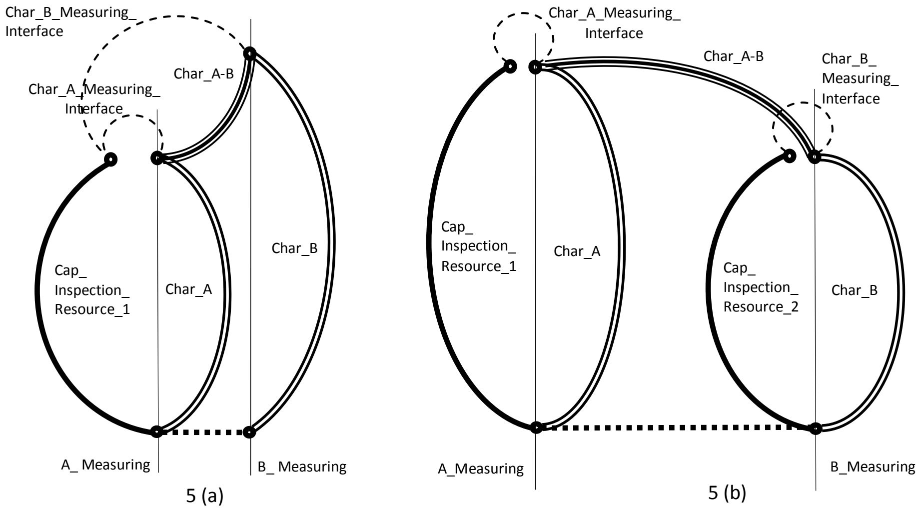

Figure 5. Graph for an indirect characteristic (Char_A-B) using: one *Inspection_Resource* (a) or two *Inspection_Resources* (b)

The *Resource_Group* that participates with a *Mechanism* role in the inspection operation is named *Inspection_Resource* (Figure 2) and is integrated by a *Machine_Base* individual, one or more *Probe* individuals and, eventually, *Fixture* individuals. The *Machine_Base* (e.g. roundness machine) is characterized by the capabilities to execute *Tool_Movement* activities, while *Probe* and *Fixture* are characterized by capabilities to execute *Tool_Part_Interaction* activities and activities concerned with locating/fixing, respectively. In the area of Geometric and Dimensional specifications (G&D), the final characteristics of the inspected part are directly determined by the G&D capabilities of the machine (resource) that executes the inspection operation and the G&D characteristics of the inspection interface, which considers the tool-part interaction (Figure 6).

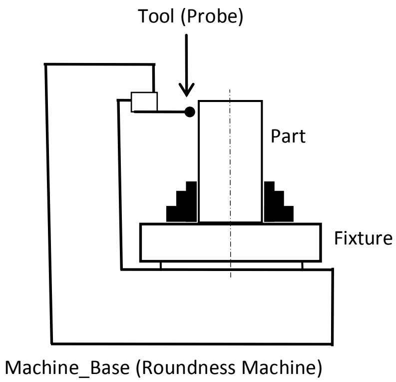

Figure 6. Physical representation of an *Inspection_Resource*

The *Resource_Group,* as a unit involved in the execution of the inspection activity with the role of mechanism, is the result of previous *Preparation* type activities that characterize the capabilities shown by the resource. The entity *Preparation* has two specializations (*Loading* and *Setup*) which are not mutually exclusive (Figure 2). This allows the existence of activities of type *Preparation* which are made up of activities of both types.

A *Loading* type activity involves the assembly of some input objects with their own characteristics. The output object will have some characteristics inherited from the input objects but it will also acquire new characteristics defining it as a unit. Figure 7 (b) shows the execution of activities of type *Loading* (*Probe_Loading* and *Stylus_Loading*), whose final result is a *Resource_Group* (*Touch_Trigger_Probe* plus *Extension*) whose characteristic (capability) is the result of the composition of the capabilities of the *Resource_Elements* that form it, the capability of the resource that executes the assembly and the characteristics of interfaces in the activity execution. Figure 7 (c) shows a simplified graph representing these two loading activities. On the other hand, a *Setup* activity type, involving measurement and correction, are performed by a resource with the mechanism role that transmits its characteristics to the resulting object. This is a type of operations that are usually done in the preparation of a inspection resource, as could be the calibration operation, usually performed with the resource itself performing a measurement on an appropriate gauge with a known uncertainty. For example, to establish the correction of a micrometer with a 25-50 mm measuring range, a gauge of 25 mm is measured with the micrometer itself.

Figure 8 shows the execution of a *Setup* activity (*Qualification*) in which the input object is the group of the resources *Coordinate_Measuring_Machine* (CMM), *Motorised_Probe_Head* (MPH) and *Touch_Trigger_Probe* plus *Extension* (TTPE), which has been the output from a previous *Loading* activity, and the resource with the mechanism role is the set formed by CMM, MPH, TTPE and spherical gauge. This resource presents a capability (Cap_SR), which can be quantified either by establishing a maximum value resulting from composition of the characteristics (capabilities) of CMM, MPH, TTPE and spherical gauge resources or by means of a calibration procedure to calculate the variability of the whole.

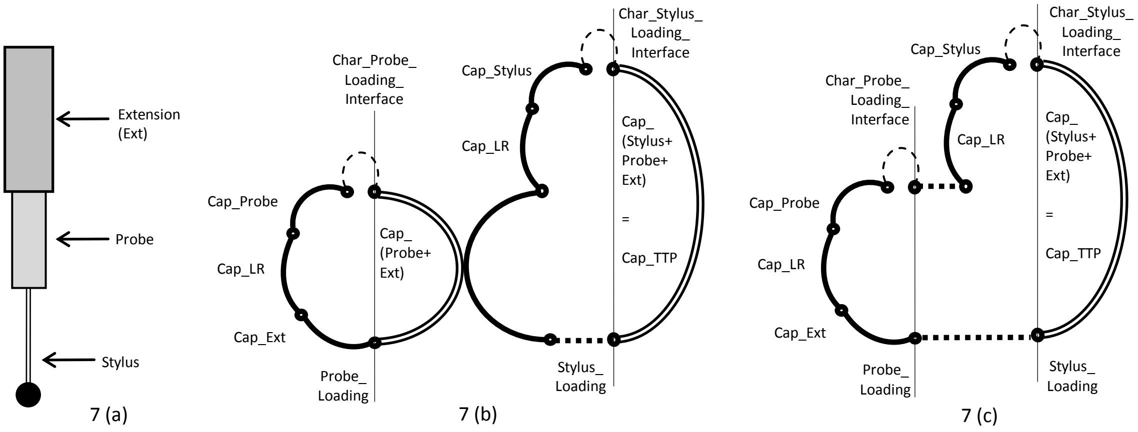

Figure 7. *Resource_group (a)*; Graph representation of preparation activities (b) and Simplified graph representation (c)

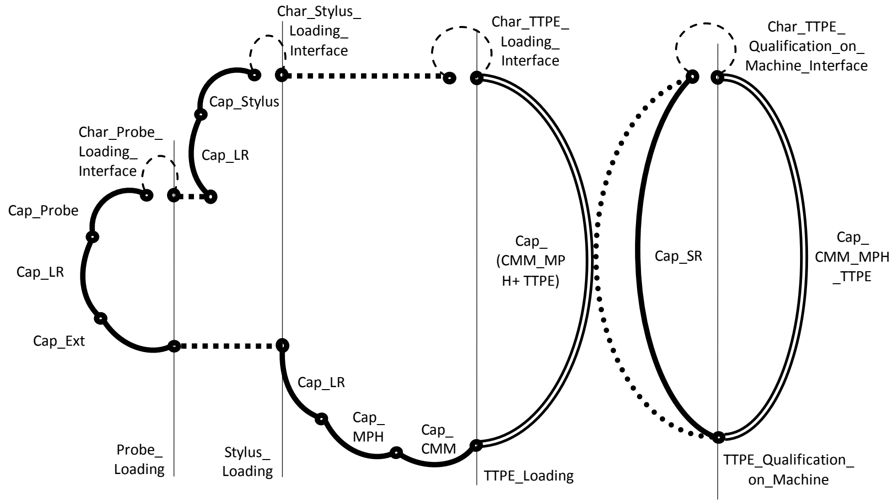

Figure 8. Characteristics graph of the *Qualification* of an *Inspection_Resource* resulting from previous *Loading* activities

4. Case study

In (Solano et al., 2015), a methodology for the validation of the resources allocated in a machining process plan was established. This methodology considers the existence of a fully or partially established process plan, and utilizes and quantifies all the characteristics associated with the execution of the preparation and operation activities of this process plan by means of graphical representations such as the ones shown in Section 3. To do this, from an initially stablished process plan, the following steps are applied: construction of the characteristics graph; identification and quantification of characteristics in the graph and improvement where necessary. In this section, the use of this methodology is extended to an inspection process plan.

Usually the definition of a process plan entails a remarkable complexity and can be performed under a combination of alternatives derived from the level of aggregation (aggregate, supervisory or operational), the approach (variant, generative or mixed) and the strategy (forward, backward or mixed) used. For any of these alternatives or combinations of alternatives it is necessary select the resources involved in the plan and validate them before his execution.

In this example the methodology identified at the beginning of the section will be applied to the configuration and selection of resources, and to the validation of the inspection plan of the part showed in Figure 9. The drawing specifies the parallelism of the hole axis (Axis) relative to the surface identified as "A" (planeA). As in previous works (Solano et al., 2015; Solano et al., 2016), the process planning tasks will be developed at supervisor level, but in this case, following a mixed strategy (fordward and backward). According to which, from the information in the drawing, the planner must select an inspection resource with capability executing an inspection of *Parallelism* type that parametrizes a region of type *Reference_Geometric_Variability* (RGV) whose value is compatible with the parallelism tolerance expressed in the drawing (0.02 mm). Applying the criterion of "the sixth of tolerance" the uncertainty in the measurement of parallelism is limited to a value not exceeding 0.0033 mm (RGV ≤ 0.0033 mm).

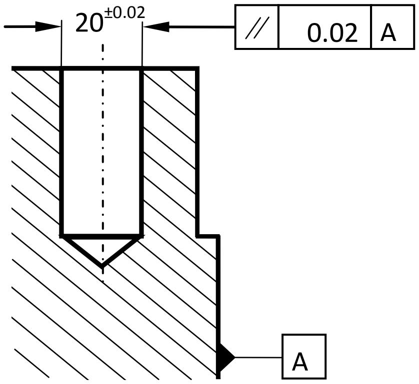

Figure 9. Geometric specification for the part

According to the proposed methodology, the planner must propose a plan that includes: (a) the activity of *Inspection* type necessary to verify the condition of parallelism expressed in the drawing and (b) the activities of *Preparation* type required for configuring the inspection resource. Considering the type of inspection, that requires a reference element (planeA) for determining axis parallelism, the starting situation is shown in the graph of Figure 10 (a), where the capability of the resource that will perform the inspection should be determined. In this first intent, for simplicity and economy, it has been assumed that the inspection is carried out with the same configuration of the resource. In Figure 10 (a) it can be seen how the capability of the resource involved in performing the two inspection activities (PlaneA_Measuring and Axis_Measuring) gives as a result the characteristics Char_PlaneA and Char_Axis, from which, indirectly, the Parallel_Axis_PlaneA characteristic is obtained.

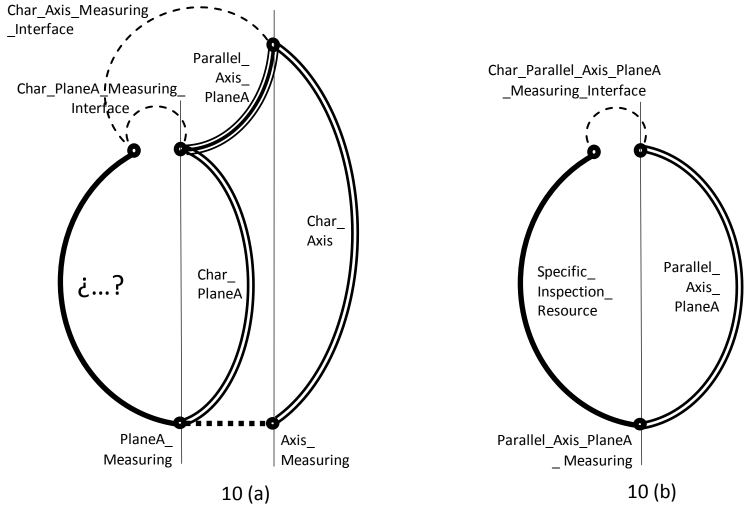

Figure 10. Characteristics graph for two alternative inspection processes

Other alternative consists in using a specific inspection resource capable for directly measuring this parallelism condition (Figure 10 (b)) such as the assembly integrated by a surface plate, a dial gauge (with double probe) and a straight edge (for the dial gauge). The surface plate, on which the A surface of the part is supported, provides reference (PlaneA) for the specification of parallelism. With the help of a support, the straight edge is oriented parallelly to the surface plate and in a direction that allows the introduction of the dial gauge in the hole. In this way, from the readings provided by the dial gauge the magnitude of the error of parallelism can be determinated. In this *Inspection_Resource*, the surface plate, with the straight edge and support for the dial gauge constitute the *Machine_Base*; the dial gauge includes the *Probe* and the surface plate is the *Fixture*.

Finally, the planner choses the first alternative process plan (indirect measurement), using three-dimensional measurement technology based on coordinate-measuring machine (CMM), because CMMs have great versatility and its use is widespread. Specifically, it is proposed to carry out the inspection with a CMM equipped with contact probes (*Touch_Trigger_Probe* or TTP). The geometry of the part requires the use of different orientations of the probe (TTP) for each of the features to inspect (PlaneA and Axis), as shown in Figure 11.

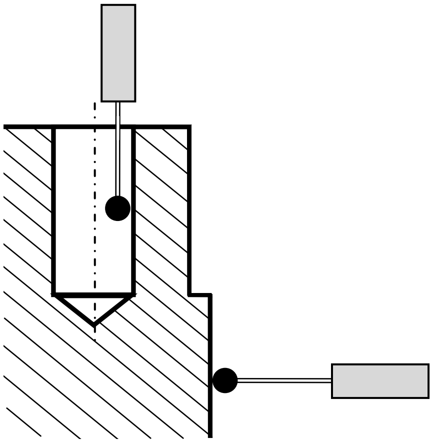

Figure 11. TTP required orientations for part inspection

The realization of both measurements could be performed with different configurations of the inspection resource considered, for example: (a) CMM with Motorised Probe Head (MPH); (b) CMM with two TTPs (Touch Trigger Probes) and (c) CMM with a TTP using a star styli (Figure 12).

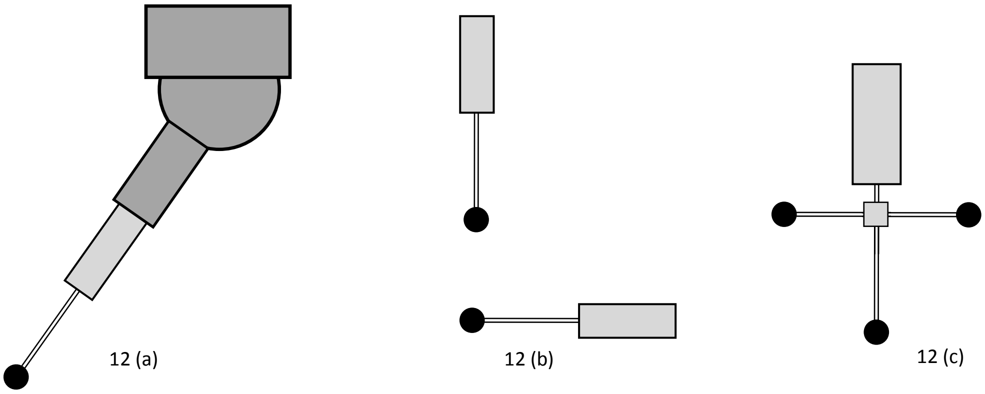

Figure 12. Alternative configurations of *Inspection_Resource* for part inspection

The first of the three options listed above is compatible with the initial assumption (a resource with the same configuration), since a CMM equipped with Motorised Probe Head (MPH) allows different orientations of the

Touch Trigger Probe (TTP). In other words, a change in the orientation of TTP as a result of the movement (rotation of MPH) is not considered a new resource configuration. In the same way that the change in position of the TTP, as a result of the movement (usually rectilinear) according to one or more of the axes of the CMM does not constitute a change in the configuration.

Next, the planner proposes the configuration CMM_MPH_TTPE1 for the inspection resource that will execute the inspection activities PlaneA_Measuring and Axis_Measuring, whose capability (Cap_CMM_MPH_TTPE1) must be compatible with the tolerance of Parallel_Axis_PlaneA (Figure 13). This resource includes Touch_Trigger_Probe1 plus Extension (TTPE1) obtained as a result of two previous *Loading* type operations as shown in Figure 8 and subsequently is mounted on the CMM with MPH (TTPE_Loading of Figure 13), where TTPE_Qualification_on_Machine setup is performed. As discussed in section 3, the outcome of this setup depends on the configuration of the resource that participates with mechanism role (CMM, MPH, TTPE1 and spherical gauge in this case).

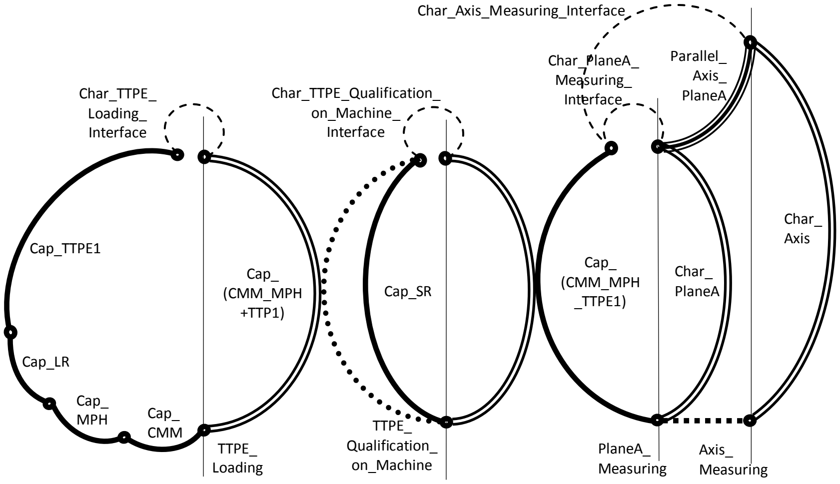

Figure 13. Characteristics graph of the inspection plan activities using a Motorized Probe Head

According to the above consideration, the uncertainties associated with the characteristics resulting from inspection activities can be quantified from the value of the uncertainty of the resource that performs the setup (qualification) and the uncertainty associated with interfaces of execution of the activities of the types *Setup* and

Inspection. Based on previous experiences, which has limited variability for these interfaces around 0.0005 mm, is assigned this value to the variability (uncertainty) of *RGV* type, while the uncertainty of the resource that participates with mechanism role in the setup (CMM_MPH_TTPE1 + spherical gauge) has RGV value of 0.0025 mm, obtained by calibration processes.

To get the uncertainties of *RGV* type associated to the rest of characteristics of the graph in Figure 14, the quadratic sum of the components are used. The uncertainty associated to Parallel_Axis_PlaneA has a value of RGV = 0.00367 mm, which exceeds the limit previously established of 0.0033 mm for the uncertainty of the resource able to inspect the specification of parallelism of the workpiece (Figure 9), whose tolerance is 0.02 mm.

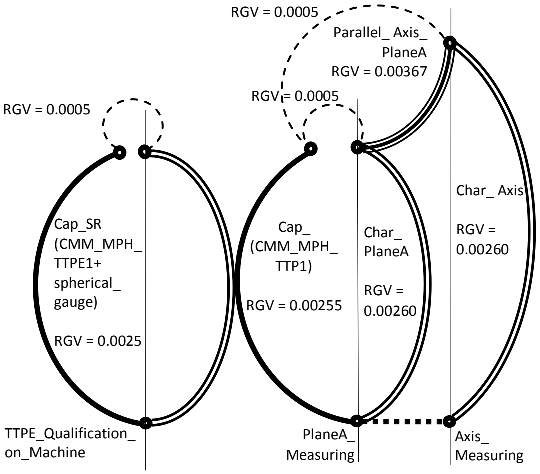

Figure 14. Quantification of the characteristics graph for inspection using a Motorized Probe Head

After analyzing these values, the planner, uses a backward strategy and proposes reduce the uncertainty associated with the characteristics Char_PlaneA and Char_Axis RGV to a value of about 0.0021 mm. Since with this value, the uncertainty in the measurement of Parallel_Axis_PlaneA characteristic would be about 0.003 mm (below the limit of 0.0033 mm). The alternative configuration shown in Figure 12 (b) is proposed, which does not require MPH nor Extension, avoiding the contribution to the uncertainty resulting from these resources. The two configurations of the inspection resource necessary in this case (horizontal and vertical disposition of TTP) have been identified as CMM_TTP1 and CMM_TTP2 in Figure 15. Taking a variability of RGV = 0.0005 mm for the interfaces, the RGV values associated with the capability of CMM_TTP1 and CMM_TTP2 resources would be of 0.002039 mm, so that their capability executing the measurements of the characteristics Char_PlaneA Char_Axis has an associated variability of RGV = 0.0021 mm. In turn, this requires a capability of the setup resource with RGV = 0.001977 mm. And finally, this implies uncertainty value of RGV = 0.001530 mm for the MPH.

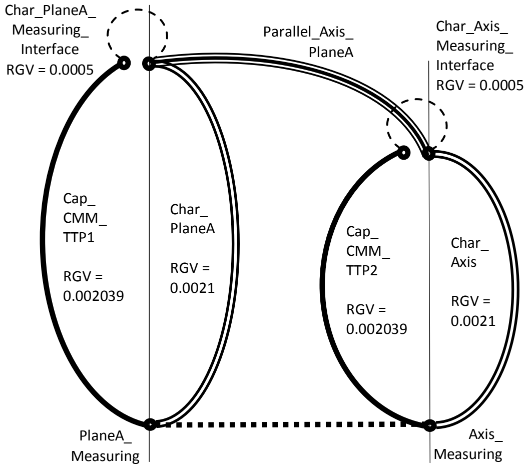

Figure 15. Characteristics graph for inspection using two Touch Trigger Probes

The catalog data for RGV values in MPH are around 0.0015 mm. The result of recalculate the rest of the values from this data (with a forward strategy) have been reflected in the graph of Figure 16, where the value of RGV = 0.003 mm for Parallel_Axis_PlaneA validates this second alternative. In it, the value of RGV = 0.002 mm for the capability of the setup resource (Cap_SR) without MPH, has been calculated considering the value of RGV = 0.0025 mm of the capability of the setup resource of the first alternative, that includes MPH (Figure 14).

Although not included in this work, it is worth noting that all the information in the graphs presented here, including their configuration, can be obtained by interrogating the ontology. Details regarding the formulation of such queries, that are constructed using the entities and relations of MIRC ontology, can be consulted at

(Solano et al., 2016).

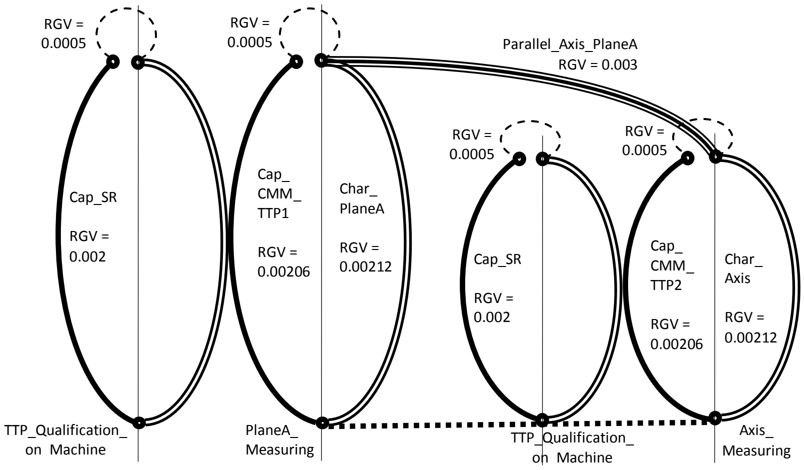

Figure 16. Quantification of the characteristics graph for inspection using two Touch Trigger Probes

Conclusion

Throughout this work, and particularly in a case study, the application of the MIRC ontology for inspection process planning and its proficiency are shown, specifically to support decision-making regarding resource planning at supervisor level: resource assignment and preparation. Similar to as was shown in the case of machining process planning, MIRC ontology enables complete validation of the plan to supervisor level, focusing on this case in the compliance of the dimensional and geometric requirements that are imposed to machined parts. Additionally, the validity of the graphical representation, previously proposed for machining process planning, has been checked in its application to inspection process planning. This graphical representation allows representing the complete inspection process plan that is formed by both activities of inspection type and activities of preparation type, including assembly and setup operations.

This similar treatment of inspection processes regarding machining processes demonstrates the validity of the MIRC ontology, the methodology and the graphical representation that supports it, to provide a basis for an integrated machining and inspection process planning. All this is based on a common conceptualization of the processes that form part of this integrated plan. With this common conceptualization, it is also demonstrated that MIRC ontology is not constituted by a closed taxonomy, because it can be extended. In the present work, this extension includes specific subclasses for the inspection, as well as some of the resources involved.

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