Semantic Representation of Robotic Function, Process Characteristics, and Quality

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Abstract

Robots in manufacturing are often described through vendor specifications, which, while important, do not fully reflect their operational performance. Equally important are the function, process characteristics, capacity, capability, and quality aspects, all of which are essential for transparent and flexible decision-making in robot selection and deployment To address this, we extend the Robot Capability Ontology (RCO), which is grounded in Basic Formal Ontology (BFO), the Industrial Ontologies Foundry (IOF) principles, the Manufacturing Service Description Language (MSDL), the Relation Ontology (RO), and the Information Artifact Ontology (IAO), to provide a semantic representation that explicitly models robotic functions, process characteristics, and quality attributes. Using the Ontology Development 101 methodology, we introduce new classes and relationships that capture the operational parameters of robotic joints, including rotational movements, speed, and angles, along with their associated measurement data. Competency questions are used to guide ontology design, while validation is performed through SPARQL queries. The Extended RCO enables a clearer distinction between function, process characteristics, and quality by supporting reasoning over robotic performance, and provides a reusable framework for transparent decision making in industrial applications.

Keywords

Autonomous Robotics, Ontological Modeling, Robot Capability, Flexible Manufacturing

1. Background and Motivation

The accurate representation of robotic function, process characteristics, and quality is becoming increasingly important in modern manufacturing, where decision making must be both flexible and transparent to adapt to diverse and evolving production demands [1]. Existing capability descriptions are fragmented, often limited to vendor specific specifications that fail to capture the operational differences between advertised and real world robotic performance [2]. To address this gap, we build on the Robot Capability Ontology (RCO) [3] [4], which is formally grounded in the Basic Formal Ontology (BFO) [5], the Industrial Ontologies Foundry (IOF) [6] principles, the Manufacturing Service Description Language (MSDL)[7], the Relation Ontology (RO)[8], and the Information Artifact Ontology (IAO) [9]. In this paper, we propose an Extended RCO that semantically models not only robotic capabilities but also their associated functions, process characteristics, and quality attributes. This extension provides a standardized, machine interpretable framework that enables manufacturing stakeholders to evaluate and compare robots beyond surface level specifications.

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A critical contribution of this work is the explicit distinction between process characteristics and quality. Process characteristics describe how a robot performs a task, capturing measurable properties such as speed, force, compliance, or repeatabilit,y while quality refers to the outcome of the process, i.e., whether the final product meets the required standards of accuracy, consistency, or finish. This distinction is necessary because a robot may exhibit excellent process characteristics yet fail to achieve the desired quality in certain contexts. For instance, in robotic painting, process characteristics include path accuracy and spray uniformity, whereas the surface finish evaluates the quality of whether it is free from streaks, uneven thickness, or overspray. Similarly, in robotic welding, process stability and repeatability influence quality; however, seam integrity and defect free joints ultimately determine whether quality standards are met. By formally representing both layers in the Extended RCO, manufacturers gain the ability to reason about not only what a robot can do but also how well it delivers the intended outcome, enabling more informed and transparent decision making in robot selection and deployment. The remainder of this short paper is structured as follows: in Section 4, we present the methodology for extending the RCO and validating the ontology using SPARQL queries in terms of completeness and coverage; in Section 4, we provide concluding remarks.

2. Extending the Robot Capability Ontology

The RCO is a reference ontology that formalises the capabilities of robots and considers the distinction between what manufacturers claim their robots can do and what they can achieve in practice.

In the following section, we discuss the RCO's development process.

2.1. Ontology Development Methodology

We utilise the Ontology development 101 methodology [10] due to its recognition within the scientific community and its ability to facilitate the reuse of existing terms and concepts. The ontology development 101 methodology involves the following steps, which guide the structured development of ontologies and the reuse of existing terms:

- Determine the domain and scope of the ontology
- Define Competency Questions (CQs)
- Consider reusing existing ontologies
- Enumerate important terms in the ontology
- Define the classes and the classes hierarchy
- Define the properties of classes
- Define the domain and range of properties
- Create instances.

We employ this methodology to extend the RCO, focusing on modeling robotic function, process characteristics, and quality. By leveraging structured steps and competency questions, the Extended RCO semantically captures these aspects in a way that is standardized, machine interpretable, and reusable. This structured extension allows for a clear distinction between the robot's functional capabilities, the measurable characteristics of its processes, and the quality of outcomes, supporting more transparent and flexible reasoning about robotic performance in manufacturing scenarios.

2.1.1. Determine Domain

The domain of our ontology is robotics in manufacturing, with a scope centered on representing and categorizing function, process characteristics, and quality of robotic systems within a production environment. This Extended RCO models robotic joints and their operational parameters, defining relevant metrics and attributes for precise assessment and establishing relationships that capture how functions, process characteristics, and quality interact in real world conditions. When developing our ontology, we chose to emphasize the practical value of our work by using real world scenario based competency questions.

2.1.2. Competency Questions

Next, we define competency questions:

- **CQ1:**What are the functions of robotic joints, and how can rotational movements be categorised in robotic systems?
- **CQ2:** What metrics and values describe the capability of a robot joint, including the units of measurement?
- **CQ3:** What process characteristics and physical qualities, such as rotational speed and angles, describe the operation of robotic joints?
- **CQ4**: What measurement data, like rotational speed and angle datums, can be linked to joints to evaluate function?

`RCO` is based on `MSDL`, a domain reference ontology created for manufacturing services and aligned with the `BFO`, `IOF`, `IAO`, and `RO`. `MSDL`'s modular structure and domain neutral classes allow `RCO` to accurately describe and expand upon robotic capabilities. Standardised terms and relationships already exist in the given in existing ontologies, giving us a strong base on which to build. Also, one of the key aspects of using the `MSDL` ontology "is that it is a significant model for representing manufacturing processes, as it captures more specific and rigorous manufacturing domain knowledge".

Once we identified the existing ontologies to reuse, we defined the different classes and their hierarchy. Then, we define each property's domain range and instantiate RCO. We start by importing existing concepts in RCO as we utilise different ontologies. The following section discusses the different terms we reused from existing ontologies and how we formalise our classes, instances, and properties under the umbrella of existing ontologies.

2.2. Enumerate Terms

Key concepts that we used from `MSDL` are: `MSDL:Equipment` class is a subclass of `MSDL:Engineered Artifact`, representing physical and digital items produced through engineering design and production techniques. We have defined the class `RCO:Handling and Transportation Equipment` within the `MSDL: Equipment` class to describe equipment specially built for material handling and transportation. we have introduced the class `RCO:Robot` as a subclass of `RCO:Handling and Transportation Equipment`, implying that robots are specific equipment for material handling and transportation in our scope.

As a result, instances such as the `RCO:NED-2 Robot` can be defined under the RCO: Robot class, indicating that it is a component of the larger domain `RCO:Handling and Transportation Equipment` and subsequently, `MSDL: Equipment`. The `IAO:Measurement Datum` class is a generic class representing measurement data. `IAO:Scalar Measurement Datum` is a subclass of `IAO:Measurement Datum`, and `IAO:Angle Measurement Datum` and`IAO:Speed Measurement Datum` are subclasses of `IAO:Scalar Measurement Datum` to define angle related measurement data properly for robot joint angles and their speed. Moreover, the object attribute `RCO:is Measurement Of` is used to represent the link between measurements and functions, quality, and process characteristics. `IAO:Measurement Datum`, a subclass of `BFO: Information Continuant Entity`, is the domain of the `RCO:is`

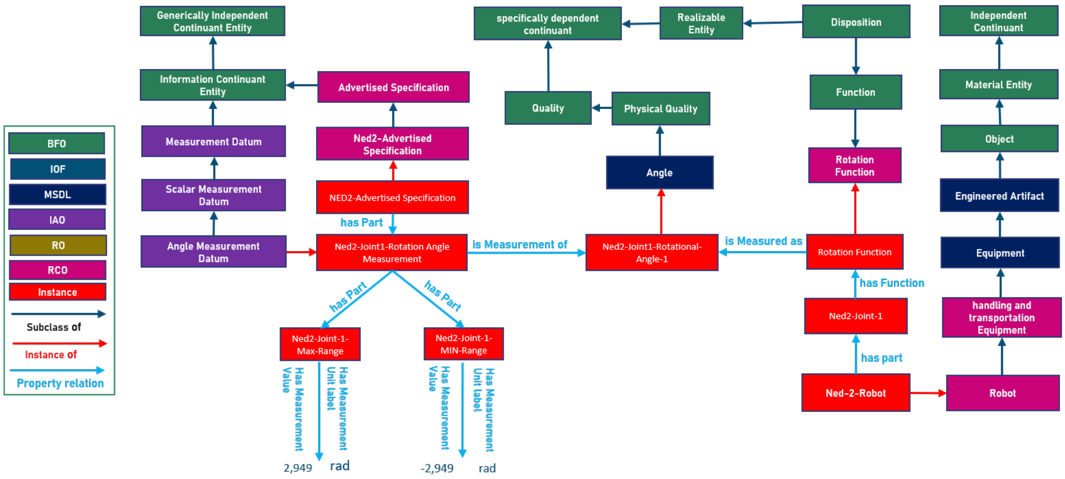

Figure 1: Function and Quality of Robot

Measurement Of, and the range of this object property is 'BFO:specifically Independent Continuant, representing the measurement's related specific independent continuant entity.

BFO relationship BFO_0000051 (has_Part) is the inverse relation of BFO:part Of, which represents the lowest and highest values of the NED2 repeatability capability and transmits measurement values, measurement data, and parameter units.

The property IAO:has measurement Unit Label shows the parameter unit's label, whereas IAO:has measurement Value associates the measurement value with a specific datum. To extend RCO to encompass more detailed aspects of robotics, particularly those related to movement and functionality, we have introduced new classes and subclasses to capture the intricate dynamics of robotic joints and their operational parameters, including their function quality and process characteristics.

To model the function of rotation specifically, we have created the class RCO:Rotation Function under the BFO class of Function, a subclass of BFO:Disposition. This structure enables us to encapsulate the inherent abilities of robotic joints to perform rotational movements as part of their overall set of functions or capabilities as shown in Fig. 1.

To provide a comprehensive model of a robotic joint as an entity within our ontology, we have introduced the class RCO:Robotic Joint. This class is a subclass of RCO:Handling And Transportation Equipment, which further connects to the broader categories of MSDL:Equipment and BFO:Engineered Artifact, and finally to BFO:Object. This hierarchical classification underscores the robotic joint's role as a critical component in the robotics domain, particularly in the context of handling and transportation equipment.

Moreover, to accurately represent the physical qualities that pertain to rotational movements, we have utilised the BFO structure, incorporating the class BFO:Quality, and under it, a subclass named BFO:Physical Quality. Within this classification, we have introduced RCO:Angle as a subclass of BFO:Physical Quality, which is crucial for understanding robotic joints' positional and orientational aspects, Second, recognising the importance of rotational movement in robotics, we have defined the class RCO:Rotational Speed, as a subclass of RCO:Speed, which is considered under the broader category of IOF:Process Profile. This categorisation allows us to address the unique aspects of speed relevant to the rotational movements found in robotic joints, specifically. To capture and represent data related to the rotational speed and angles of robotic joints, we have established two specific measurement datum classes; The class RCO:Rotational Speed Measurement Datum is created as a subclass of IAO:Speed Measurement Datum, which in turn is a subclass of IAO:Measurement Datum. Similarly, the class RCO:Rotational Angle Measurement Datum is defined under IAO:Rotational Measurement Datum, also a subclass of IAO:Measurement Datum as shown in Fig. 2.

Through these enhancements to our ontology, we aim to offer a more nuanced and detailed framework for understanding and modeling robotic joints' functionalities, qualities, and process characteristics,

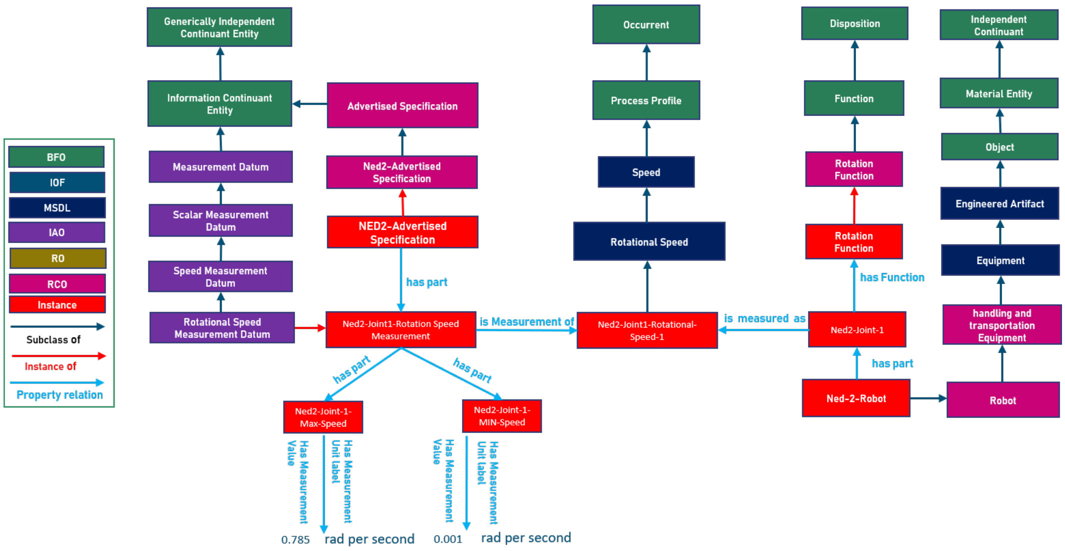

Figure 2: Function and Process Profile

mainly focusing on their ability to perform rotational movements. This enhanced model facilitates a deeper exploration of robotics' capabilities and operational dynamics, paving the way for more sophisticated applications and analyses in the field of manufacturing.

3. Ontology Validation Using SPARQL

A thorough evaluation was conducted to confirm that the proposed ontology in terms of coverage and completeness. (CQ4) was validated through a corresponding SPARQL query.
SPARQL Query for CQ4:

```
SELECT ?measurement ?part ?value ?unit

WHERE {
RCO:NED2-Joint-1 obo:IAO_0000417 ?measurement .
    ?measurement obo:BFO_0000051 ?part .
    OPTIONAL { ?part obo:IAO_0000004 ?value . }
    OPTIONAL { ?part obo:IAO_0000039 ?unit . }

}
```

This structured query allows the ontology to provide precise information about the joint's physical properties, with results visualized in Fig. 3.

This SPARQL query answers the competency question regarding the measurements of the robotic joint *NED2-Joint-1*. It retrieves the joint's associated measurements, relevant parts, numerical values, and units. The property `obo:IAO_0000417` links the joint to its measurements, while `obo:BFO_0000051` optionally identifies associated parts. Measurement values and units are obtained via `obo:IAO_0000004` and `obo:IAO_0000039`, respectively.

4. Conclusion

RCO captures a robot's functions, process characteristics, and quality parameters enables precise, consistent, and reusable access to critical information. It supports informed robot selection, performance

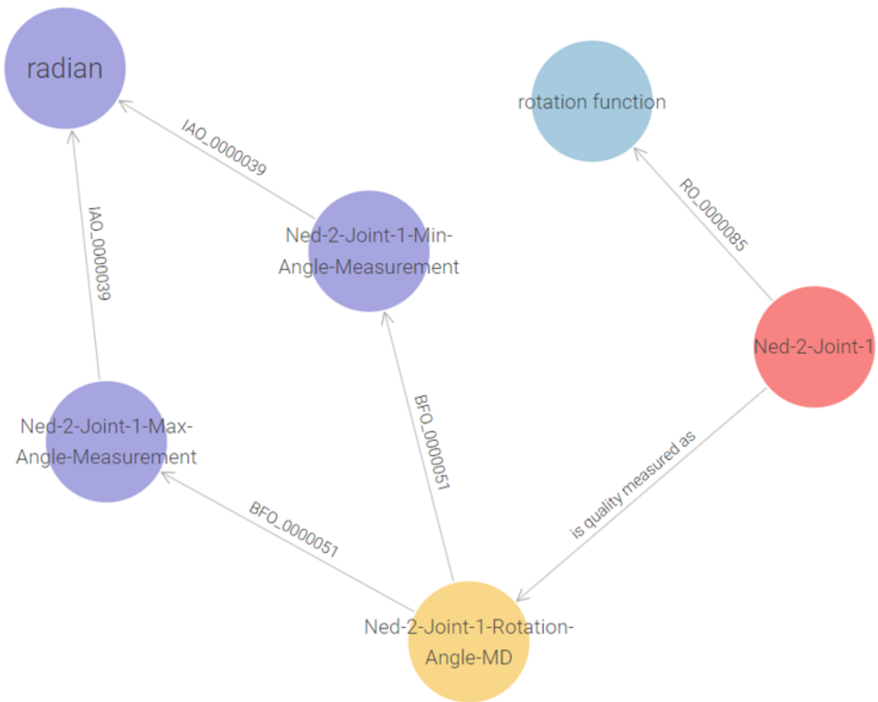

Figure 3: Function and Process Profile

evaluation, and task planning while providing explainable reasoning for decisions, thereby enhancing transparency and trust in robotic systems. This helps manufacturers make informed decisions on robot selection, optimize processes, and ensure reliable performance.

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Declaration on Generative AI

Generative AI tools were used solely to assist with language editing and refinement of the manuscript. The authors take full responsibility for the accuracy, originality, and integrity of the work.

Disclaimer

Since September 2024, Mohamed Hedi Karray has joined European Innovation Council and SMEs Executive Agency. The views expressed in this publication are the responsibility of the authors and do not necessarily reflect the views of the European Commission nor of the European Innovation Council and SMEs Executive Agency. The European Commission, the European Innovation Council, and SMEs Executive Agency are not liable for any consequences stemming from the reuse of this publication.

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