Do robots know enough about their collaborative and adaptive events? Rethinking OCRA - An ontology for Collaborative Robotics and Adaptation

Alberto Olivares-Alarcos[1], Sergi Foix[1], Stefano Borgo[2] and Guillem Alenyà[1]

Abstract— **In the near future, robots shall collaborate with humans, overcoming uncertainty and safety constraints during the execution of industrial robotic tasks. Hence, reliable collaborative robots must be capable of reasoning about their collaboration's specifications (e.g. safety), and also the adaptation of their plans due to unexpected situations. A common approach to reasoning is to represent the domain knowledge using logic-based formalisms, such as ontologies. In this article, we revisit OCRA, an Ontology for Collaborative Robotics and Adaptation, which was built around two main notions: collaboration, and plan adaptation. OCRA assures a trusty human-robot collaboration, since robots can model and reason about their collaborations and plan adaptations in collaborative robotic scenarios. However, the ontology can be improved: a more thorough discussion of the concept of adaptation's trigger can help to understand adaptations. Hence, we posit a new research question to extend OCRA, and propose a definition for adaptation trigger.**

I. INTRODUCTION

Through the last few years, there has been a growing interest in more flexible industrial processes where robots and humans work as a team. For this reason, some robots (collaborative robots, or co-bots) have been especially designed for direct interaction with humans within a collaborative workspace [1]. When one develops industrial processes where robots and humans truly collaborate, it is common to find several issues related to uncertainty and safety. Hence, it is desirable that collaborative robots can reason about their tasks' requirements (e.g. safety, performance, etc.), about the changes in their environment, and about the plan's adaptations that might be triggered by those changes.

Industrial collaborative robotics has lately attained much attention in research [2], [3], [4]. For instance, safety in collaborative robotic scenarios has been addressed in several works [5], [6], [7], [8]. Meanwhile, other researchers have developed adaptive robotic solutions for industrial applications [9], [10], [11]. The large number of interesting works also presents some drawbacks. There is a lack of agreement about the meaning of concepts such as collaboration and adaptation, which has hindered the coherent development of methodologies and techniques. Indeed, using ambiguous terminology in safety applications (e.g. assessing risks) may lead to confusion and mistaken implementations [5].

Knowledge representation formalisms such as ontologies [12], are useful approaches to harmonizing terminology and allowing its reusability. Indeed, the use of ontologies is becoming usual in the industrial domain as shown by large projects like OntoCommons, IOF and the UK National Digital Twins[1]. The IEEE Standards Association is supporting standardization projects for robotics an automation. For example, the 1872–2015 IEEE Standard Ontologies for Robotics and Automation [13], and the 1872.2-2021 IEEE Standard for Autonomous Robotics Ontology [14]. These standardization efforts are currently being extended to other robotics' sub-domains [15]. Furthermore, ontologies have been widely used for autonomous robotics during the last years [16], and we can even find some initial steps towards ontologies for collaborative robotics [17], [18]. Nevertheless, there is still room for improvement, for instance, these ontologies can be extended to other applications.

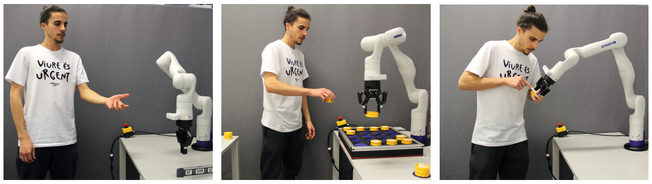
In this article, we revisit OCRA, an Ontology for Collaborative Robotics and Adaptation [18]. The ontology formalizes the domain knowledge in *collaborative scenarios* where robots *adapt* their plans' executions to the unexpected changes in the environment. OCRA has already been validated and used to reason about the knowledge involved in collaborative tasks such as those shown in Fig. 1. Here, we question the coverage of the ontology and propose a new direction along which to extend the knowledge that OCRA is able to capture and model. For instance, in OCRA which type of situations can trigger adaptations is not analyzed in depth. A classification of these situations is relevant to understand how and why adaptations occur. We present here a research question and a set of competency questions to set the basis for an extension of OCRA. Finally, we provide an initial definition of `Adaptation Trigger`.

II. RELATED WORK

The 1872–2015 IEEE Standard Ontologies for Robotics and Automation [13], and the 1872.2-2021 IEEE Standard for Autonomous Robotics Ontology [14] were conceived as references for knowledge representation and reasoning in the domain. They include a formal vocabulary for humans and robots to share knowledge about robotics and automation. However, they did not cover terminology for particular robotic sub-domains. Hence, several ontology-based systems for autonomous robots were implemented focusing on more specific notions. Some examples are Knowrob [19], [20],

[1]Institut de Robòtica i Informàtica Industrial, CSIC-UPC, Llorens i Artigas 4-6, 08028 Barcelona, Spain.
[2]Laboratory for Applied Ontology (LOA), ISTC-CNR, Trento, Italy.

[1]`https://ontocommons.eu/`
`https://www.industrialontologies.org/`
`https://digitaltwinhub.co.uk/ndtp/`



(a) (b) (c)

Fig. 1: (a) A collaboration in which the human is stopped asking the robot for a tool. (b) A kitting task in which the human and the robot collaboratively fill a tray with tokens. (c) A collaborative piece insertion in which the robot and the human exchange forces.

ORO [21], PMK [22], CARESSES [23], and ADROn [24], [25]. These works have explored and proven the relevance and usefulness of ontologies in robotics. However, they do not address the problems tackled by OCRA.

Other authors have focused on industrial robotic applications. Stenmark et al. [26], proposed the ROSETTA ontology, aimed at supporting reconfiguration and adaptation of robot-based manufacturing cells. Balakirsky [27] implemented an ontology-based system for automatic recognition and adaptation to changes in manufacturing workflows. Stipancic et al. [28], proposed to use a set of ontologies to semantically enrich the robot's sensors data in order to enhance the decision-making process in a multi-agent scenario. Chen et al. [29], presented an ontology for automatic disassembly applications to represent terms related to processes, tools and production pieces such as fasteners. Unfortunately, none of these works provided a formal analysis and definition for the terms discussed in OCRA, although these are relevant for their domains.

Of special interest is the work of Umbrico et al. [30], who defined an ontology for human-robot collaboration. They focus on notions which are quite different from those of OCRA. Indeed, both ontologies could coexist and complement each other. The clear overlap regards the notion of `Collaboration`. The definition in OCRA is better characterized and more general as it comes from a thorough analysis of how the concept is used in the literature. Hence, it provides a perspective which is ontologically-based and that comprehensive of the view shared by most works in literature, including [30]. Furthermore, OCRA integrates other notions central to talk about adaptability such as `Collaboration Place` and `Plan Adaptation`.

Finally, there are also several works about ontologies for the industrial domain in general [31], [32], [33], [34], [35], [36], [37]. Nonetheless, the notions defined in OCRA are not modeled in any of them.

III. OCRA - ONTOLOGY FOR COLLABORATIVE ROBOTICS AND ADAPTATION

In this article, we discuss about the need for extending some of the concepts defined in OCRA [18]. Thus, we start by introducing the core of OCRA.

A. Methodology

The development of OCRAfollowed a top-down approach, building it upon other higher-level ontologies. Specifically, the work relied on ontological analysis, an approach that precedes the usual ontology construction process and aims to fix the core framework for the domain ontology. This choice led to perform a series of steps: to set the ontology domain and scope (competency questions), to evaluate other conceptualizations (selection of relevant literature), to enumerate, analyze and compare existing concepts (identification of shortcomings), to develop and formalise a more solid conceptualisation, and to create instances of the concepts and show their use (implementation/validation). As a final step, the documentation and maintenance of the proposal was taken into account.

B. Scope, goal and competency questions

OCRA was conceived to be compliant with the most widely used knowledge-based framework for robots, Knowrob [19], [20]. Hence, OCRA adopted the same ontology used in Knowrob, i.e., the DOLCE+DnS Ultralite (DUL), which is based on the Dolce foundational ontology [38]. The scope of the ontology covers the domain knowledge in collaborative robotics, with special attention to collaboration and robot plan's adaptations. Specifically, OCRA was aimed to answer the following questions:

- Ontology coverage questions:
  - **C1** - What is a collaboration?
  - **C2** - What is a plan adaptation?
- Competency questions:
  - **Q1** - Which and how many collaborations are running now?
  - **Q2** - Which is the plan of a collaboration?
  - **Q3** - Which is the goal of a collaborative plan?
  - **Q4** - Are these agents collaborating?
  - **Q5** - Where is a collaboration happening?
  - **Q6** - How is a collaboration classified (e.g. non-physical)?
  - **Q7** - Which is the risk of a collaboration?
  - **Q8** - Which and how many plan adaptations are running now?
  - **Q9** - Which is/are the agent/s participating in the plan adaptation?
  - **Q10** - Why is an adaptation of an agent's plan happening?
  - **Q11** - Which is the plan before and after an adaptation?
  - **Q12** - Which is the goal of the agent involved in the adaptation that is also the goal to be achieved by both the old and the new plan?

C. Natural language definitions and formalization

Several informal and formal definitions from the literature were studied and compared, discrepancies and commonalities where highlighted, and the need for a thorough formal model

Ref.	Formal	Goal	Plan	Interaction /Execution
[1]	No	-	-	Yes
[5]	No	Yes	-	Yes
[39]	No	Yes	Yes	Yes
[40]	Yes	Yes	-	Yes
[41]	No	Yes	Yes	Yes
[42]	No	Yes	-	-
[43]	No	Yes	Yes	Yes
[44]	No	Yes	Yes	Yes
[17]	Yes	Yes*	Yes*	-
Ours	Yes	Yes	Yes	Yes

TABLE I: Main aspects related to 'Collaboration' extracted from the literature. 'Formal' indicates whether the literature definition was formalized. 'Goal', 'Plan' and 'Interaction/Execution' columns indicate whether the notion of each aspect was captured by the definition. *Implicit in the definition.

for `Collaboration` (see Table I) and `Adaptation` (see Table II) was motivated.

Usually, `Collaboration` is described as a special kind of spatio-temporal entity (an event). Moreover, it is often related to a goal and a plan, and it requires interaction among the agents. Hence, `Collaboration` was defined as *'an event in which two or more agents share a goal and a plan to achieve the goal, and execute the plan while interacting'*.

In the state-of-the-art definitions about `Adaptation`, some patterns emerge: adaptation shall be triggered by a stimulus, shall occur on an entity that would change to a new state, and shall aim to continuously pursue the achievement of a goal. From the literature, it becomes clear that providing a general definition of `Adaptation` is extremely challenging. Barandiaran et al. [45], discussed that adaptation involves a norm specifying which is the appropriate change to make. Hence, depending on the type of norm, one could find different types of adaptations: task or plan-based, evolutionary, ecological, etc. The focus in OCRA is on plan-based adaptations, changes aimed at continuously pursuing the completion of a plan's goal given an unexpected state or situation. Finally, `Plan Adaptation` was defined as *'an event in which one (or more) agent, due to its evaluation of the current or expected future state, changes its current plan while executing it, into a new plan, in order to continuously pursue the achievement of the plan's goal.'*

Centered around these two main concepts, OCRA also defines related notions such as `Collaboration Place`, `Collaboration Risk`, and different types of collaborations.

D. Formalization of the ontological classes

The OCRA ontology is formalized in First Order Logic (FOL) and in OWL 2 DL, a description logic version of OWL 2 (Web Ontology Language). FOL's expressivity allows to completely capture the meaning behind the different notions defined in natural language. The formalization in OWL 2 DL served to deploy the ontology into a robot for run-time reasoning. The latter formalization is accessible at[2].

[2]`www.iri.upc.edu/groups/perception/OCRA`

Ref.	Formal	Trg.	Ent.	Chg.	Goal
[46]	No	-	Yes	Yes	-
[47]	Yes**	Yes	Yes	Yes	Yes
[48]	No	-	Yes	Yes	Yes
[49]	No	Yes	Yes	Yes*	Yes*
[50]	No	Yes	Yes	Yes*	-
[51]	No	Yes	Yes	Yes*	-
Ours	Yes	Yes	Yes	Yes	Yes

TABLE II: Main aspects related to 'Adaptation' extracted from the literature. 'Formal' column indicates whether the literature definition was formalized. 'Trg.' (trigger), 'Ent.' (entity), 'Chg.' (change) and 'Goal' columns indicate whether the notion of each aspect was captured by the definition. *Implicit in the definition. **The model is mathematical but not ontology-based.

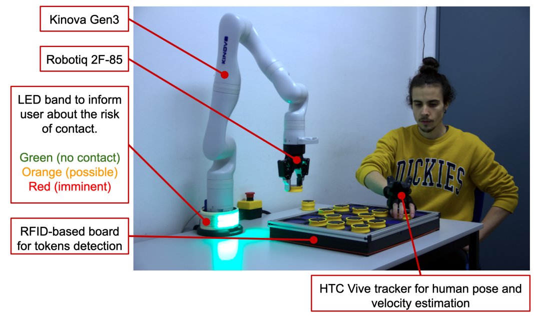


Fig. 2: Lab mock-up of a real task, where a robot and a human share the task of filling the compartments of a tray.

E. Validation - Competency questions and limit cases

First, a validation of the ontology's capabilities to answer the set of competency questions proposed in Sec III-B was carried out. Note that the competency questions were the design prerequisites of the ontology. Therefore, a good test is to answer them, proving that the ontology was properly formalized, and that it meets the desired requirements. Specifically, the competency questions were contextualized within different situations extracted from a proposed collaborative scenario (see Fig. 2). For each case, an OWL 2 DL knowledge base was used containing the proper instances to answer the queries. Being able to reason over OCRA using an inference engine (HermiT [52]), also validated that the ontology was consistent and coherent.

In a second validation, the robustness of the proposed ontological model was studied. This was based on the analysis of OCRA's performance in several limit cases of the formalization. Particularly, a set of examples was considered. These are events that might be classified as `Collaborations` or `Plan Adaptations` but contain incongruent or incomplete knowledge (axioms). The analysis of the formal definitions in FOL and OWL 2 DL in these cases showed whether OCRA was able to exclude the incorrect instances. The results confirmed that the formal definitions within OCRA allowed to exclude the limit cases in most of the cases [18]. This validation proved the strength of the formal model in situations where it might be unclear whether an event is or not a `Collaboration` or a `Plan Adaptation`.

It is worth noting that OCRA has the potential to be used within robotic architectures to help in decision-making processes. For instance, using OCRA, a robot may infer that a collaboration ceases to exist because the human and the robot no longer share the goal or the plan. Hence, the robot could decide to ask the human to solve the issue. This use of the ontology has not been validated yet.

IV. DISCUSSION: A CLOSER LOOK TO THE TRIGGER OF PLAN ADAPTATIONS

OCRA states that a plan adaptation happens due to an unexpected situation that makes a new plan better than the one that an agent (robot) is executing. However, the ontology does not get into the details of the nature of that adaptation's trigger. We realized that it may be interesting to perform an ontological analysis around the types of situations that can produce the need for adapting a plan. In particular, we are interested in answering the following research question:

- What are the necessary ontological classes to classify the unexpected outcomes that trigger robot's plan adaptations, and what are the criteria to classify a situation in one or another?

A. Ontological scope

The scope of our intended OCRA's extension covers the classes of situations that might trigger a robot plan adaptation. Of course, the ontology is framed in the collaborative robotics domain, but we would like to consider broader applications. The initial set of competency questions that we propose to tackle are:

CQ1 - What is an adaptation trigger and how is it classified?

CQ1a - Which agent is realizing an adaptation trigger?

CQ1b - Which is the plan before realizing an adaptation trigger?

CQ1c - Which is the plan after the adaptation?

CQ1d - Which is the goal to be achieved by both plans?

CQ2 - During the execution of a plan, what is the relevant knowledge from the robot's observation viewpoint that triggers an adaptation?

CQ2a - Which are the objects that have a role in triggering an adaptation?

CQ2b - Which are the objects' properties (qualities or relationships) that have a role in triggering an adaptation?

CQ2c - How are those objects' properties related to what is described in the (initial) plan?

CQ3 - During the execution of a plan, how does the relevant knowledge for the adaptation trigger relate to the robot plan's description (e.g. task expectations)?

CQ3a - How does the relevant knowledge for the adaptation trigger relate to the expected preconditions of the next task to be executed in the initial plan?

CQ3b - How does the relevant knowledge for the adaptation trigger relate to the expected postconditions of the last task that has been executed in the initial plan?

CQ3c - How does the relevant knowledge for the adaptation trigger relate to the expected postconditions of the next task to be executed in the initial plan?

CQ3d - How does the relevant knowledge for the adaptation trigger relate to the goal to be achieved by executing the plan?

B. Ongoing work

We have started working on a definition for `Adaptation Trigger`. One of the main ideas was to relax the definition of `Plan Adaptation`, in which the adaptation exists if the second plan is executed. We thought that an `Adaptation Trigger` must exist even before the new plan is executed. For us, an `Adaptation Trigger` is *'an agent's evaluation of the current or an expected future state, making the agent change its current plan while it is being executed, into a new plan, in order to continuously pursue the achievement of the plan's goal.'* Our intention is to continue working on this definition and its formalization.

V. CONCLUSION

In this article, we revisited OCRA, an Ontology for Collaborative Robotics and Adaptation. It was built considering two main notions: collaboration, and plan adaptation. The ontology was formalized in FOL for its expressivity and in OWL 2 DL for its computational benefits. OCRA development represents a step forward to more trustworthy collaborative robots, and also promotes the interoperability and reusability of the terminology in the domain. Here, we discussed how the ontology could be extended. Specifically, the notion of trigger of a `Plan Adaptation` was not deeply analyzed in our previous work. Hence, in this article we proposed a new research question and delimited the goal of a potential extension of OCRA. In the future, we aim to formalize the notion of `Adaptation Trigger` and its different sub-classes. The extended ontology will be validated following a similar approach to the one used to validate the initial version of OCRA. Furthermore, we would like to use the ontology in other scenarios, not necessarily involving industrial tasks.

ACKNOWLEDGMENT

This work is supported by MCIN/ AEI /10.13039/501100011033 and by the "European Union NextGenerationEU/PRTR" under the projects ROB-IN (PLEC2021-007859) and COHERENT (CHIST-ERA PCI2020-120718-2). Stefano Borgo acknowledges support by the European project OntoCommons (GA 958371, `ontocommons.eu`). A. Olivares-Alarcos is supported by the European Social Fund and the Ministry of Business and Knowledge of Catalonia through the FI 2020 grant.

REFERENCES

[1] I. ISO, *10218 Robots and robotic devices-Safety requirements for industrial robots - Part 2: Robot systems and integration*, 2011.

[2] R. Gervasi, L. Mastrogiacomo, and F. Franceschini, "A conceptual framework to evaluate human-robot collaboration," *The International Journal of Advanced Manufacturing Technology*, vol. 108, pp. 841–865, May 2020.

[3] L. Gualtieri, E. Rauch, and R. Vidoni, "Emerging research fields in safety and ergonomics in industrial collaborative robotics: A systematic literature review," *Robotics and Computer-Integrated Manufacturing*, vol. 67, p. 101998, 2021.

[4] W. Kim, L. Peternel, M. Lorenzini, J. Babič, and A. Ajoudani, "A human-robot collaboration framework for improving ergonomics during dexterous operation of power tools," *Robotics and Computer-Integrated Manufacturing*, vol. 68, p. 102084, 2021.

[5] F. Vicentini, "Terminology in safety of collaborative robotics," *Robotics and Computer-Integrated Manufacturing*, vol. 63, p. 101921, 2020.

[6] V. Gopinath, K. Johansen, M. Derelöv, Åke Gustafsson, and S. Axelsson, "Safe collaborative assembly on a continuously moving line with large industrial robots," *Robotics and Computer-Integrated Manufacturing*, vol. 67, p. 102048, 2021.

[7] H. Liu and L. Wang, "Collision-free human-robot collaboration based on context awareness," *Robotics and Computer-Integrated Manufacturing*, vol. 67, p. 101997, 2021.

[8] A. Olivares-Alarcos, S. Foix, and G. Alenyà, *Human-Robot Collaboration: Unlocking the potential for industrial application*, ch. Time to Contact for Robot Safety Stop in Close Collaborative Tasks, pp. 1–17. The Institution of Engineering and Technology, to appear.

[9] S. Levine and B. Williams, "Concurrent plan recognition and execution for human-robot teams," *Proceedings of the International Conference on Automated Planning and Scheduling*, vol. 24, pp. 490–498, May 2014.

[10] S. J. Levine and B. C. Williams, "Watching and acting together: Concurrent plan recognition and adaptation for human-robot teams," *Journal of Artificial Intelligence Research*, vol. 63, pp. 281–359, 2018.

[11] V. Villani, L. Sabattini, F. Loch, B. Vogel-Heuser, and C. Fantuzzi, "A general methodology for adapting industrial hmis to human operators," *IEEE Transactions on Automation Science and Engineering*, pp. 1–12, 2019.

[12] S. Borgo, A. Galton, and O. Kutz, "Foundational ontologies in action. Understanding foundational ontology through examples," *Applied ontology*, vol. 17, no. 1, pp. 1–16, 2022.

[13] C. Schlenoff, E. Prestes, R. Madhavan, P. Goncalves, H. Li, S. Balakirsky, T. Kramer, and E. Migueláñez, "An ieee standard ontology for robotics and automation," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1337–1342, 2012.

[14] P. J. Gonçalves, A. Olivares-Alarcos, J. Bermejo-Alonso, S. Borgo, M. Diab, M. Habib, H. Nakawala, S. V. Ragavan, R. Sanz, E. Tosello, and H. Li, "Ieee standard for autonomous robotics ontology [standards]," *IEEE Robotics & Automation Magazine*, vol. 28, no. 3, pp. 171–173, 2021.

[15] S. R. Fiorini, J. Bermejo-Alonso, P. Gonçalves, E. Pignaton de Freitas, A. Olivares Alarcos, J. I. Olszewska, E. Prestes, C. Schlenoff, S. V. Ragavan, S. Redfield, B. Spencer, and H. Li, "A suite of ontologies for robotics and automation [industrial activities]," *IEEE Robotics Automation Magazine*, vol. 24, no. 1, pp. 8–11, 2017.

[16] A. Olivares-Alarcos, D. Beßler, A. Khamis, P. Goncalves, M. K. Habib, J. Bermejo-Alonso, M. Barreto, M. Diab, J. Rosell, J. Quintas, J. Olszewska, H. Nakawala, E. Pignaton, A. Gyrard, S. Borgo, G. Alenyà, M. Beetz, and H. Li, "A review and comparison of ontology-based approaches to robot autonomy," *The Knowledge Engineering Review*, vol. 34, p. e29, 2019.

[17] A. Umbrico, A. Orlandini, and A. Cesta, "An ontology for human-robot collaboration," *Procedia CIRP*, vol. 93, pp. 1097 – 1102, 2020. 53rd CIRP Conference on Manufacturing Systems 2020.

[18] A. Olivares-Alarcos, S. Foix, S. Borgo, and Guillem Alenyà,, "Ocra – an ontology for collaborative robotics and adaptation," *Computers in Industry*, vol. 138, p. 103627, 2022.

[19] M. Tenorth and M. Beetz, "Knowrob – knowledge processing for autonomous personal robots," in *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4261–4266, IEEE, 2009.

[20] M. Beetz, D. Beßler, A. Haidu, M. Pomarlan, A. K. Bozcuoğlu, and G. Bartels, "Knowrob 2.0 — a 2nd generation knowledge processing framework for cognition-enabled robotic agents," in *2018 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 512–519, 2018.

[21] S. Lemaignan, R. Ros, L. Mösenlechner, R. Alami, and M. Beetz, "Oro, a knowledge management platform for cognitive architectures in robotics," in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 3548–3553, 2010.

[22] M. Diab, A. Akbari, M. Ud Din, and J. Rosell, "PMK—A Knowledge Processing Framework for Autonomous Robotics Perception and Manipulation," *Sensors*, vol. 19, 2019.

[23] B. Bruno, N. Y. Chong, H. Kamide, S. Kanoria, J. Lee, Y. Lim, A. K. Pandey, C. Papadopoulos, I. Papadopoulos, F. Pecora, *et al.*, "The caresses eu-japan project: making assistive robots culturally competent," in *Italian Forum of Ambient Assisted Living*, pp. 151–169, Springer, 2017.

[24] F. Ramos, A. S. Vázquez, R. Fernández, and A. Olivares-Alarcos, "Ontology based design, control and programming of modular robots," *Integrated Computer-Aided Engineering*, vol. 25, no. 2, pp. 173–192, 2018.

[25] F. Ramos, C. O. Scrob, A. S. Vázquez, R. Fernández, and A. Olivares-Alarcos, "Skill-oriented designer of conceptual robotic structures," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 5679–5684, 2018.

[26] M. Stenmark and J. Malec, "Knowledge-based instruction of manipulation tasks for industrial robotics," *Robotics and Computer-Integrated Manufacturing*, vol. 33, pp. 56 – 67, 2015.

[27] S. Balakirsky, "Ontology based action planning and verification for agile manufacturing," *Robotics and Computer-Integrated Manufacturing*, vol. 33, pp. 21 – 28, 2015.

[28] T. Stipancic, B. Jerbic, and P. Curkovic, "A context-aware approach in realization of socially intelligent industrial robots," *Robotics and Computer-Integrated Manufacturing*, vol. 37, pp. 79 – 89, 2016.

[29] W. H. Chen, G. Foo, S. Kara, and M. Pagnucco, "Automated generation and execution of disassembly actions," *Robotics and Computer-Integrated Manufacturing*, vol. 68, p. 102056, 2021.

[30] A. Umbrico, A. Cesta, G. Cortellessa, and A. Orlandini, "A holistic approach to behavior adaptation for socially assistive robots," *International Journal of Social Robotics*, vol. 12, pp. 617–637, Jul 2020.

[31] J. S. Liang, "An ontology-oriented knowledge methodology for process planning in additive layer manufacturing," *Robotics and Computer-Integrated Manufacturing*, vol. 53, pp. 28 – 44, 2018.

[32] V. R. Sampath Kumar, A. Khamis, S. Fiorini, J. L. Carbonera, A. Olivares-Alarcos, M. Habib, P. Goncalves, H. Li, and J. I. Olszewska, "Ontologies for industry 4.0," *The Knowledge Engineering Review*, vol. 34, p. e17, 2019.

[33] M. H. Karray, F. Ameri, M. Hodkiewicz, and T. Louge, "Romain: Towards a bfo compliant reference ontology for industrial maintenance," *Applied Ontology*, vol. 14, pp. 155–177, 2019. 2.

[34] B. Smith, F. Ameri, H. Cheong, D. Kiritsis, D. Sormaz, C. Will, and J. N. Otte, "A first-order logic formalization of the industrial ontology foundry signature using basic formal ontology." 2019.

[35] S. Borgo, A. Cesta, A. Orlandini, and A. Umbrico, "Knowledge-based adaptive agents for manufacturing domains," *Engineering with Computers*, vol. 35, pp. 755–779, Jul 2019.

[36] M. Mohd Ali, R. Rai, J. N. Otte, and B. Smith, "A product life cycle ontology for additive manufacturing," *Computers in Industry*, vol. 105, pp. 191 – 203, 2019.

[37] J. S. Liang, "A process-based automotive troubleshooting service and knowledge management system in collaborative environment," *Robotics and Computer-Integrated Manufacturing*, vol. 61, p. 101836, 2020.

[38] S. Borgo, R. Ferrario, A. Gangemi, N. Guarino, C. Masolo, D. Porello, E. M. Sanfilippo, and L. Vieu, "DOLCE: A descriptive ontology for linguistic and cognitive engineering," *Applied Ontology*, vol. 17, pp. 45–69, March 2022.

[39] O. for Economic Co-operation and Development, *PISA 2015 assessment and analytical framework: Science, reading, mathematic, financial literacy and collaborative problem solving*. OECD Publishing, 2017.

[40] F. F. Oliveira, J. C. Antunes, and R. S. Guizzardi, "Towards a collaboration ontology," in *Proc. of the Snd Brazilian Workshop on Ontologies and Metamodels for Software and Data Engineering*, João Pessoa, 2007.

[41] P. Dillenbourg, *Collaborative learning: Cognitive and computational approaches. (Advances in learning and instruction series)*, ch. 1 -

What do you mean by collaborative learning?, pp. 1–19. PO Box 945, Madison Square Station, New York, NY 10160-0757: Elsevier Science Ltd., 1999.

[42] B. G. Silverman, "Human-computer collaboration," *Human-Computer Interaction*, vol. 7, no. 2, pp. 165–196, 1992.

[43] L. G. Terveen, "Overview of human-computer collaboration," *Knowledge-Based Systems*, vol. 8, no. 2-3, pp. 67–81, 1995.

[44] G. L. Kolfschoten, *Theoretical foundations for collaboration engineering*. PhD thesis, Faculty of Technology Policy and Management. Delft University of Technology., Jaffalaan 5, 2628 BX Delft, the Netherlands, 12 2007. A.

[45] X. E. Barandiaran, E. D. Paolo, and M. Rohde, "Defining agency: Individuality, normativity, asymmetry, and spatio-temporality in action," *Adaptive Behavior*, vol. 17, no. 5, pp. 367–386, 2009.

[46] E. Järvenpää, M. Lanz, R. Tuokko, *et al.*, "Application of a capability-based adaptation methodology to a small-size production system.," *International Journal of Manufacturing Technology and Management*, vol. 30, no. 1/2, pp. 67–86, 2016.

[47] J. A. Martín H., J. de Lope, and D. Maravall, "Adaptation, anticipation and rationality in natural and artificial systems: computational paradigms mimicking nature," *Natural Computing*, vol. 8, p. 757, Aug 2008.

[48] T. Lints, "The essentials of defining adaptation," in *2010 IEEE International Systems Conference*, pp. 113–116, 2010.

[49] B. Smit and J. Wandel, "Adaptation, adaptive capacity and vulnerability," *Global Environmental Change*, vol. 16, no. 3, pp. 282 – 292, 2006.

[50] B. Smit, I. Burton, R. J. Klein, and J. Wandel, "An anatomy of adaptation to climate change and variability," *Climatic Change*, vol. 45, pp. 223–251, Apr 2000.

[51] E. Gjorven, F. Eliassen, and J. O. Aagedal, "Quality of adaptation," in *International Conference on Autonomic and Autonomous Systems (ICAS'06)*, pp. 9–9, 2006.

[52] B. Glimm, I. Horrocks, B. Motik, G. Stoilos, and Z. Wang, "Hermit: An owl 2 reasoner," *Journal of Automated Reasoning*, vol. 53, pp. 245–269, Oct 2014.