Comparison of Dependencies for Human-Robot Interaction Types

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Abstract

Typically, four types of human-robot interaction are distinguished: Coexistence, Synchronization, Cooperation, and Collaboration. They differ in the degree of interaction between human and robot and have therefore high impact on safety requirements for a system. Leading to human-robot cooperation and collaboration systems rarely being introduced in industrial practice due to the high risks associated with them. An underlying problem for this, is the lack of understanding for the differences and necessities of these interaction types on a conceptual level. In this paper, we investigate the differences between the four human-robot interaction types with respect to the dependencies between human and robot. Although in all interaction types humans and robots depend on each other, we show that these dependencies are very different in nature. For future use cases, this analysis helps in binding safety risks to concrete properties of the human-robot dependencies.

Keywords

Human-Robot Interaction, Goal Modeling, Dependencies, Interaction Types

1. Introduction

To enhance performance, both industry and academia have been continuously endeavoring to develop and refine self-assessment models capable of evaluating organizations' readiness for Industry 4.0 [1]. The integration of intelligent robotics systems is seen as a pivotal factor to achieve this goal since it enhances efficiency, flexibility, and overall productivity of modern manufacturing landscapes [2]. For all of these reasons, in the last years, research efforts have been directed towards a modular robotics with the goal of improving Industry 4.0 readiness [3].

The integration of intelligent robotic systems in Industry 4.0 along with the support of human-robot interaction (HRI) is seen as a key driver to reduce production costs while simultaneously improving product quality, particularly for producing small batch sizes or highly individualized products [4].

HRI is the field of designing, understanding, and evaluating robotic systems, that involves humans and robots interacting through communication [5]. Safety during HRI is vital, especially the safety of the human, namely, the safe interaction between operators and collaborative robots [6]. In current practice, the introduction of collaborative systems is often hindered by insufficient

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understanding of the safety implications resulting from the interactions between human and robot in direct collaborative scenarios [7]. Therefore, we see a rising introduction of human-robot interaction, focusing on a clear separation between the working spaces of human and robot. At the same time, the benefits of collaborative environments are seen as a key for further advancing of flexible manufacturing.

In this paper, we contribute an investigation of the dependencies between human and robot. To do so, we use goal models to highlight the differences in dependencies between human and robot for different interaction types. We conclude by proposing a framework of human-robot dependencies that relate to different HRI types. This allows gaining a deeper understanding of the nature of human-robot interaction and its different manifestations (i.e. the different HRI types). It, furthermore, allows the development of systematic approaches to specify HRI and to assess the risks attached to the different dependencies.

The paper is structured as follows, Section 2 gives an overview of the related work. Section 3 investigates the dependencies that exist in different types of HRI. Section 4 then discusses and evaluates the differences in the previously investigated dependencies. Section 5 then concludes the paper along with possible future work.

2. Foundations and Related Work

2.1. Types of Human-Robot Interaction

The field of HRI lacks consensus on the terminology used to classify the different types of interactions between humans and robots [8]. We refer to Bauer et al.'s [9] categorization of interaction types, as it covers numerous different modalities and is widely used in the field.

The various interaction types are illustrated in Figure 1 and are described in brief below:

- **Human-robot Coexistence** is a type of interaction where both human and robot work in separated workspaces without any protective fences between them [10]. There exist no direct contact between the human and the robot, as both work on separate components in their respective workspaces.
- **Human-robot Synchronization** is the type of interaction where both human and robot work on the same component in the same workspace, but not at the same time. They can have access to the workspace and component one after the other. The contact between them is unnecessary and should be avoided.
- **Human-robot Cooperation** is the type of interaction where both human and robot work on different components in the same workspace and at the same time. The contact between human and robot might occur due to working in the same workspace, but it is unnecessary.
- **Human-robot Collaboration** is the type of interaction where both human and robot work on the same component in the same workspace and at the same time. The contact between human and robot is necessary.

2.2. Goal Modeling

Goal modeling is an established approach in requirements engineering [11] and addresses the goals from the very early stages of development [12], already allowing the reasoning of concepts and different solution alternatives [13]. Common goal modeling approaches are iStar [14, 15, 16], GRL [17] (a light-weight standardized version of iStar) and KAOS [18, 19].

Goal models provide a systematic approach to displaying stakeholder or system goals in their context. The goals capture, at different levels of abstraction, the various objectives the system under consideration should achieve[20]. The iStar framework is, among others, beneficial in capturing and analyzing properties of complex systems in terms of actors, their intentions, and their relationships [21]. Goal models emphasize the relation between the various elements, which allows one to specify the hierarchical decomposition of goals, contributions, and dependencies. GRL and iStar have already been shown to be useful for modeling robotic systems in early phases (e.g., [22]). For instance, Morales et al. [23] use iStar to successfully specify teleo-reactive robots. Their extension is later on systematically integrated into the work by Gonçaleves et al. [24].

In previous work, we proposed the use of a lightweight GRL-compliant iStar extension to model collaborative cyber-physical systems [25]. Among the chosen system types to which the extension was applied, a fleet of collaborative transport robots used in a modern factory for evaluation. In more recent work, we extended this goal modeling extension to support safety analyses of human-robot collaborations [26, 22] and the specification of digital twins for human-robot collaboration systems [27].

3. Investigating Dependencies in Human-Robot Interaction

In this paper, we investigate what dependencies exist in different HRI scenarios. We, therefore, compare how dependencies differ for the four types of HRI: Coexistence, synchronization, cooperation, and collaboration. To do so, we introduce and then analyze a case example from the industry domain that includes all four types in one assembly process.

3.1. Case Example

To visualize the differences and maintain relation to the real world, we chose a small scale industry case example from the manufacturing domain, the assembly of a toy truck. The idea is that the truck is assembled on a collaborative workspace, where a human and a cobot work together in close proximity. A projector is used to display instructions for the human to follow, and it also displays boundaries of the workspaces for the human, the cobot and the area for both human and cobot. During the assembly of the toy truck, different human-robot interaction scenarios are applied, which correspond to four types of human-robot interaction: coexistence, synchronization, cooperation, and collaboration as shown in Figure 1. A detailed explanation of the tasks involved in the assembly process for each interaction type is provided in the subsections 3.2, 3.3, 3.4 and 3.5

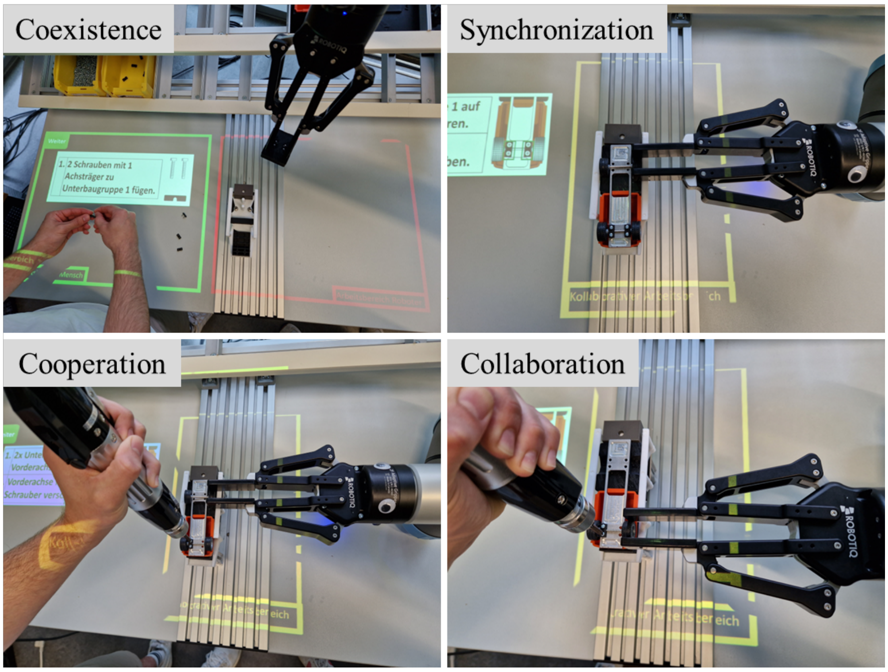

Figure 1: Coexistence: The human prepares the axle holders while the cobot places the load carrier, with each working in their own workspace. Synchronization: The cobot places the rear axle in the shared workspace, exits. The human waits until the cobot exits and then enters to screw the axle holders. Cooperation: The human screws the front axle while the cobot places the rear axle. Collaboration: The cobot holds the front axle while the human screws it in.

3.2. Human-Robot Coexistence

While the human prepares four axle holders by inserting two screws in each holder, the robot assembles the base of the truck by inserting the cabin, the load carrier, and the chassis into the mounting bracket. Figure 2 shows the goal model for this interaction type. There exist no new dependencies except the normal ones between the actors during the execution tasks, as there is currently no communication between them.

3.3. Human-Robot Cooperation

Figure 3 shows the goal model with assembly tasks specific to human-robot cooperation. Once the cobot is done placing the front axle, the human starts fixing it with the two prepared axle holders. Simultaneously, the cobot moves on to picking and placing the rear axle. When the cobot has placed the rear axle, the human starts screwing an axle holder to the left and right of the rear axle. The cobot's pick and place of the second axle and the human's screwing of the first two axle holders in the shared workspace can happen simultaneously. The interaction is therefore cooperative, since the tasks are executed in the shared workspace at the same time, but not on the same component.

Unlike human-robot coexistence (as shown in Figure 3), human and cobot communicate.

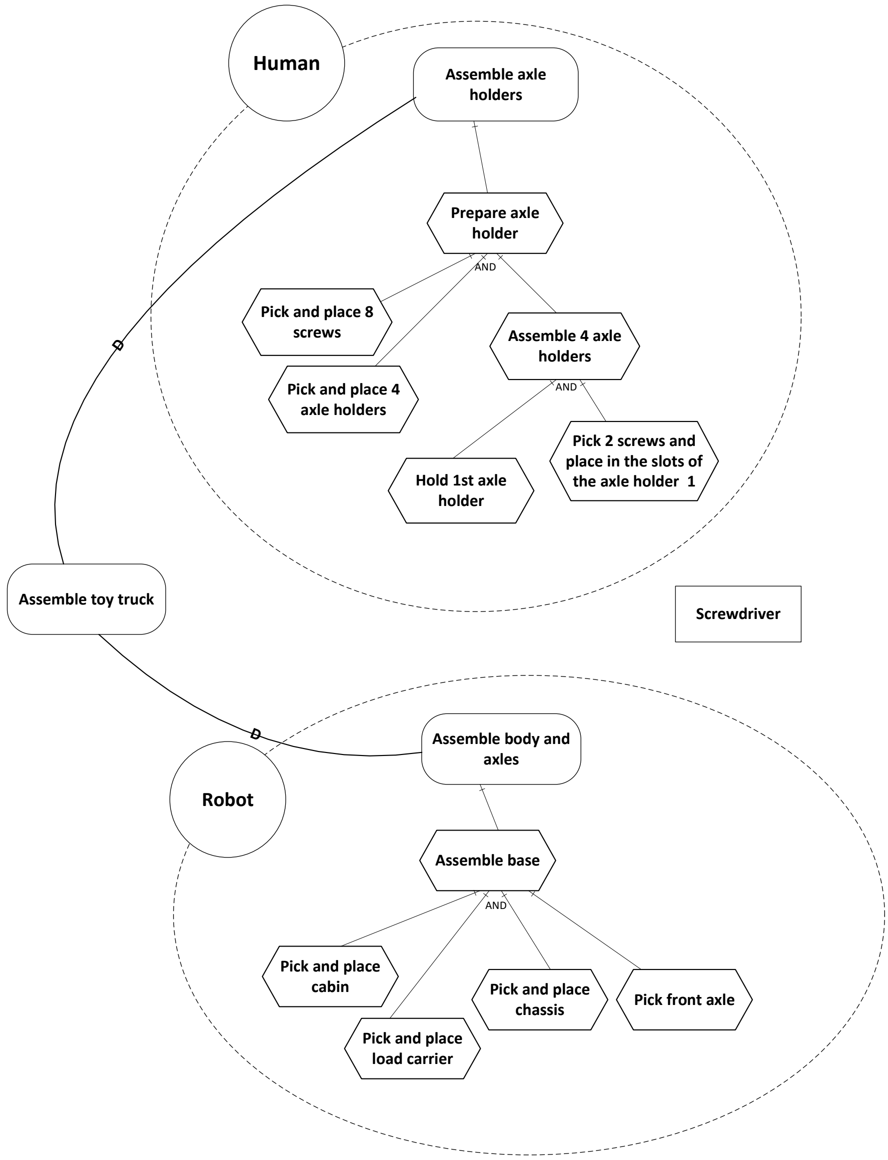

Figure 2: Dependencies in human-robot coexistence

Certain tasks of the cobot are dependent on the tasks of the human and vice versa. These tasks are not necessarily bidirectional. The dependencies here illustrate how one actor must wait for the other actor to complete a task on a certain component. If there are different components involved, there exist no dependency between both actors. For example, the task of the actor human 'Place one axle holder on the left of rear axle' is dependent on the task of the actor cobot 'Place rear axle in the back of the chassis' meaning the cobot has to finish working on the part 'rear axle' before the human could start working on it.

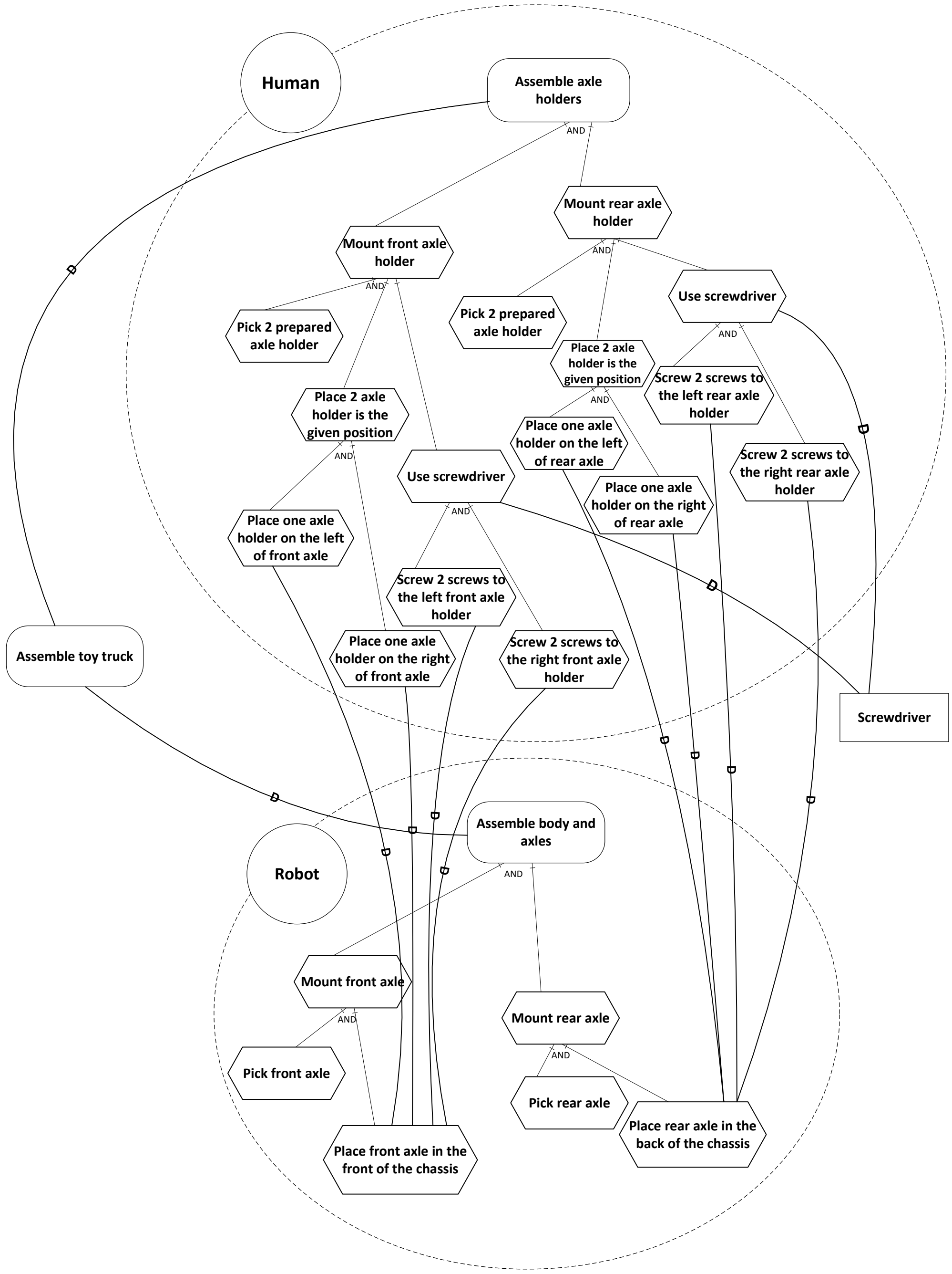

Figure 3: Dependencies in human-robot cooperation

3.4. Human-robot Synchronization

Figure 4 shows the tasks for human-robot synchronization and collaboration. The process for human-robot synchronization is similar to that of human-robot cooperation. The difference is

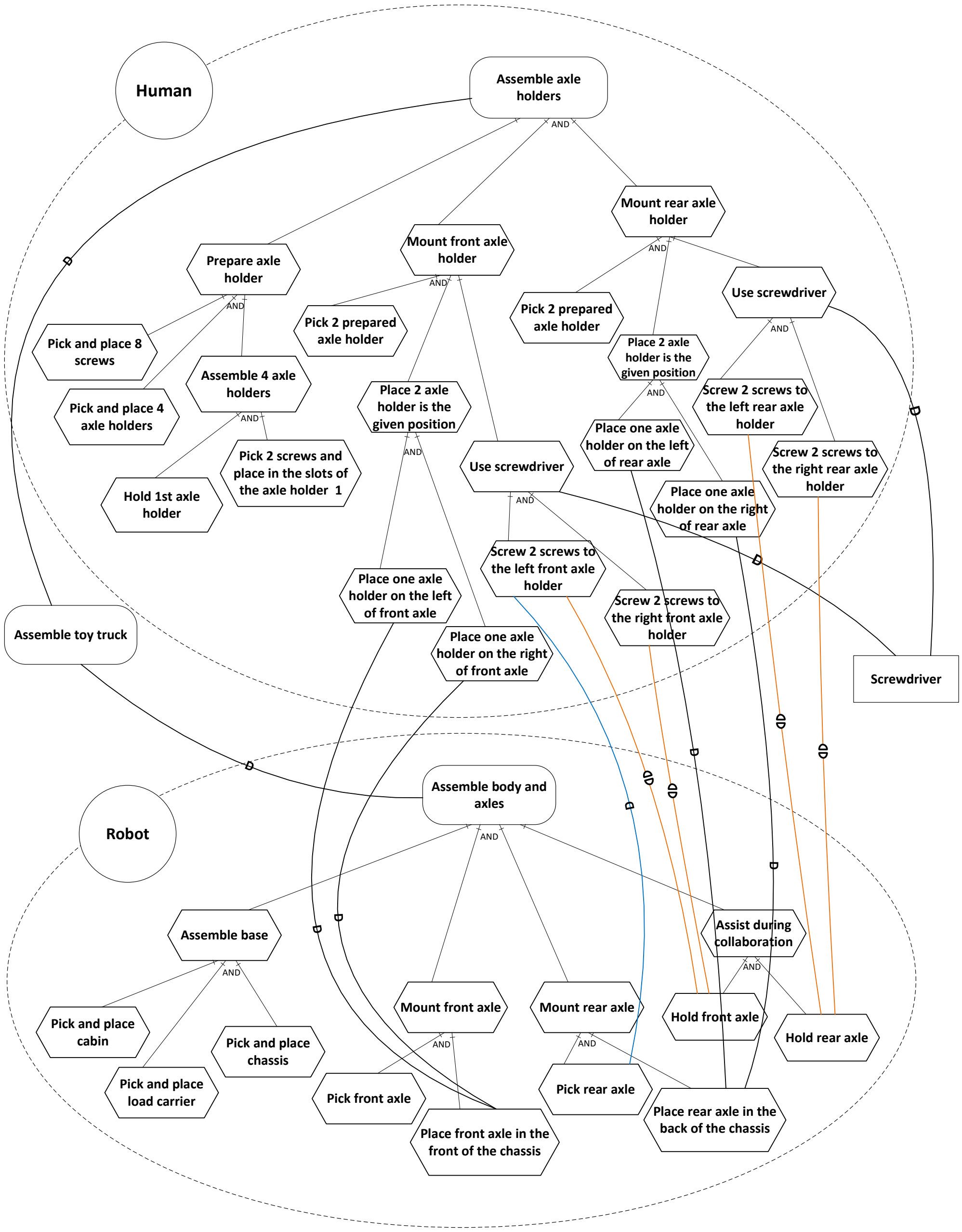

Figure 4: Dependencies in human-robot synchronization (blue) and collaboration (orange)

that, unlike cooperation, synchronization requires maintaining spatial restrictions. The human is not allowed to enter the shared workspace while the robot is working in the said workspace and vice versa. After the cobot picks and places the front axle, it moves out of the shared workspace. The human then enters the workspace and screws two axle holders to the left and right of the front axle. The human again leaves the area so that the cobot can place the rear axle. It is then mounted in the same way.

In Figure 4, the dependency shown in color blue is the one representing human-robot synchronization. The dependencies are considered from the fact that when the human is working in the shared area, the cobot is not allowed to enter the area and when the cobot is working, the human is not allowed to enter the shared area. For example, task ‘Place one axle holder on the right of front axle’ is dependent on ‘Place front axle in the front of the chassis’. Another example is that the task of the actor cobot ‘Place rear axle in the back of the chassis’ is dependent on the task of the human ‘Screw 2 screws to the right front axle holder’. The dependency explained here states that one task has to be completed for the second task to begin. Another dependency type states that the task must be completed, and the human must exit the shared workspace for the robot to enter and perform its task, and vice versa. Synchronization is restricted in comparison to cooperation due to these dependencies.

3.5. Human-robot Collaboration

Human-robot collaboration differs from those for human-robot synchronization and cooperation, as an additional task of holding the axles is performed by the robot while the human is screwing the axle holders. After the cobot picks and places the front axle, it holds the axle in place for the human to screw the axle holders. Once both the axle holders are fixed, the cobot then moves on to performing the next task. The rear axle is then assembled the same way. Thus, for collaboration, human and cobot are working in the shared area, on the same component and at the same time.

In figure 4, the dependencies for human-robot collaboration are shown in the color orange. When the robot is holding and the human is screwing, both the human and robot are working together, which means they are working on the axles of the truck at the same time in the shared workspace. This is specified in the goal model, with a bidirectional dependency between tasks like ‘Screw 2 screws to the right rear axle holder’ of the human and ‘Hold rear axle’ of the robot. Another example of the bidirectional dependency can be seen between the task ‘Screw 2 screws to the left front axle holder’ and ‘Hold front axle’. The collaboration also involves an active interaction where the task of robot ‘Pick rear axle’ is dependent on the task of the human ‘Screw 2 screws to the left front axle holder’ which means the robot cannot pick the rear axle until the human is done screwing the axle holder to the right of the front axle.

4. Dependencies in Human-Robot Interaction

4.1. Identified Dependency Types in HRI

In human-robot coexistence, there exist no dependency between the actors human and robot. As for the rest, the dependencies depend on the sequence of execution of tasks and the restrictions of the workspace. In human-robot synchronization, tasks are performed one after the other by both actors, stating one actor has to wait for the other actor to finish a task. The actor also has to wait for the other actor to leave the part and the shared workspace for them to perform their own tasks.

In summary, for human-robot synchronization, two different dependency types need to be distinguished: **process sequence dependencies** and **spatial dependencies**. Process sequence dependencies refer to dependencies resulting from the assembly process (i.e. one task has to be finished before another task can be performed). Spatial dependencies result from the sharing of the workspace (e.g., the human must have left the workspace, before the cobot is allowed to enter).

For human-robot cooperation, again **process sequence dependencies** are as seen for human-robot synchronization, as the tasks of both actors depend on other tasks to be executed by that time. As human and cobot do not work on the same component at the same time, it is not necessary to leave the shared workspace. However, it is necessary to observe **spatial time dependencies**, which differ from those used in human-robot synchronization. The actors are not dependent on a cleared space; rather, they must adapt their behavior when the other actor is present. For example, a robot must work more slowly if the human is present in a certain area.

In human-robot collaboration, both actors are dependent on each other when performing a task on a part in the shared area. Thus, we see **bidirectional synchronization dependencies**, where both actors need to synchronize to work on a task at the same time. Thus, the work of the cobot depends on the human and vice versa. In addition, we again have **process sequence dependencies** and **spatial time dependencies** for certain tasks.

In summary, five types of dependencies to be differentiated to properly describe and differentiate HRI are identified:

- **Normal dependency**: In addition, to the dependencies related to HRI, normal dependencies still exist, which are known from other system types as well. For instance, actors or tasks being dependent on the availability of a resource. In this paper, we do not discuss these normal dependencies to avoid confusion with the dependencies related to the HRI types.
- **Process sequence dependency**: Dependency rooted in the production process, where one task can only be executed after the successful completion of another task.
- **Spatial dependency**: Dependency where a task by one actor can only be executed if the workspace has been prepared, meaning the actor who performed the previous task has vacated the workspace, allowing the current actor complete access to the entire area.
- **Spatial time dependency**: Behavioral dependency, where the tasks of two actors are interdependent and must adhere to specific time related conditions during their execution.
- **Bidirectional synchronization dependency**: Dependency where a task by one actor is dependent on a task by another actor, and reciprocally, that task by the other actor is dependent on the task by the first actor.

Figure 5 visualizes the different dependency types and their relations to the different HRI types using a simplified GRL meta-model based on [15]. We introduce the actors human and collaborative robot, which are central for HRI. In addition, the four newly identified dependency types are highlighted.

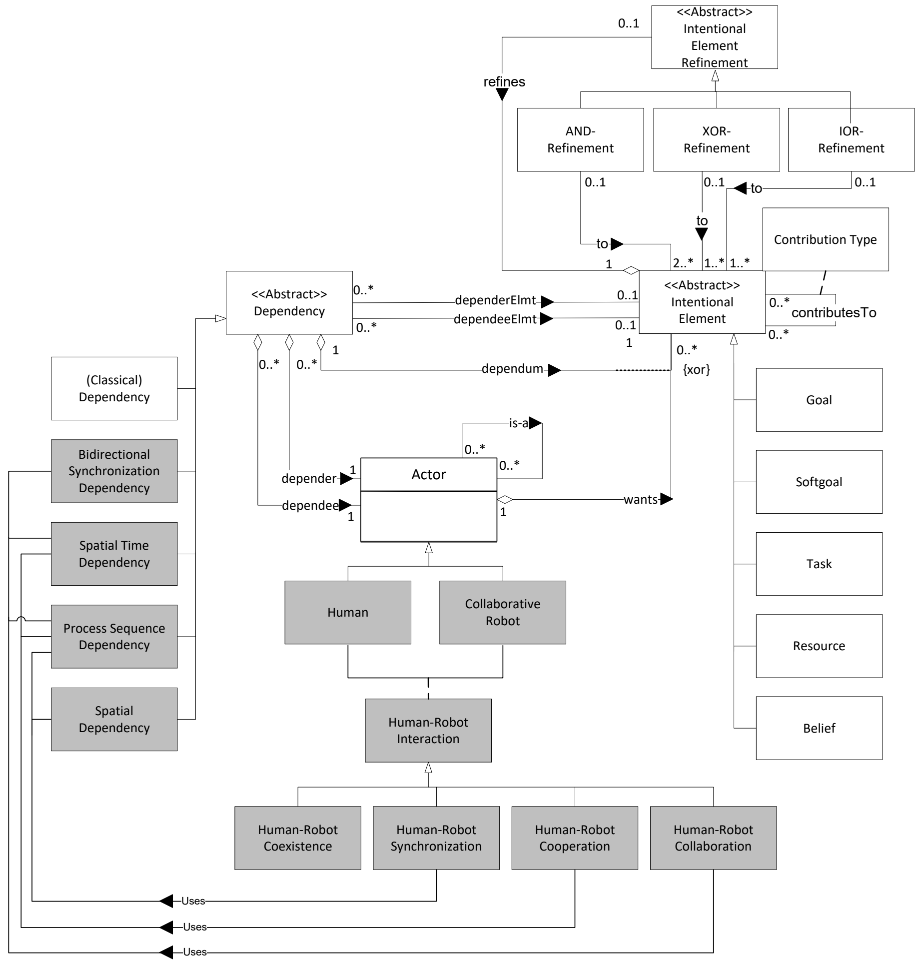

Figure 5: Interaction Types and Dependency Types in the GRL meta-model

4.2. Discussion

A comparative analysis of the interdependencies between humans and robots reveals that the specific interdependencies involved vary depending on the interaction type. While only the normal dependencies need to be taken into account for coexistence, synchronization also involves process sequence and spatial dependencies, and cooperation involves process sequence and spatial time dependencies. In the context of collaboration, the same dependencies that apply to cooperation are also relevant, with the additional consideration of bidirectional dependencies (Figure 5).

It is essential to consider the potential safety risks associated with each dependency between humans and robots when performing tasks together. Therefore, it is crucial to identify these dependencies at the outset of the assembly sequence planning process, including how they may be influenced by the choice of interaction modality. Goal models offer a straightforward method for identifying task-specific dependencies and the overall number of dependencies to be considered in the assembly process. This approach allows planning experts to evaluate the relative merits of different interaction modalities, taking into account the additional effort required to manage dependencies at the task level within the assembly process.

5. Conclusion and Future work

In future manufacturing scenarios, HRI is crucial, as evidenced by increasing research in this area. Despite strong research interest in intensive human-robot collaborations involving physical contact, there is reluctance in industry applications due to safety concerns and a lack of understanding of how these interactions affect each other. This paper investigates the differences in dependencies between humans and robots across various interaction types.

In general, it is accepted, that there are four major types of HRI: Coexistence, Synchronization, Cooperation, and Collaboration, each varying in the degree of interaction and dependencies between humans and robots. In this paper, we used goal models to investigate the dependencies between human and robot for the different types of HRI. We conclude that there exist different types of dependencies as well. These dependencies can be categorized into four types excluding the normal dependency: Process sequence, Spatial, Spatial Time, and Bidirectional, which are based on the sequence of task execution and workspace restrictions. Process sequence refers to the order in which tasks are performed, spatial to the physical workspace shared, spatial time to the timely behavior in shared workspaces, and bidirectional to mutual communication. We then showed how these relate to the interaction types. It can be said that we do not have a 1:1 relation between interaction types and dependency types. However, not every dependency type is used for every interaction type and vice versa. Which we believe to have an impact on the safety assessment of the HRI types and needs to have an influence on structured approaches to develop human-robot interactions.

Understanding and managing these dependencies is crucial for ensuring both the safety and successful completion of tasks in HRI. These factors play a significant role in designing efficient workflows and enhancing the overall synergy between human workers and robotic systems. For the future, safety and potential threats must be taken into account concerning these types of dependencies. Therefore, an extensive analysis on the correlation between the dependency and the safety must be conducted. In addition, generalizability of our findings must be assured by application to different use cases in HRI. Furthermore, HRI are also used outside the manufacturing domain, for which transferability of the results to other domains (e.g., service robotics) should be proved.

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