Classification of collaboration levels for human-robot cooperation in manufacturing

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Abstract. Industry 4.0 aims to support the factory of the future, which involves increased amounts of information systems and new ways of using automation. One new usage is collaboration between human and industrial robot in manufacturing, with both partners sharing work on a single task. Supporting human-robot collaboration (HRC) requires understanding the requirements of HRC as well as the differences to existing approaches where the goal is more automation, such as in the case of self-driving cars. We propose a framework that we call *levels of collaboration* to support this, and posit that this framework supports a mental model conducive to the design of lines incorporating HRC.

Keywords. Human-robot collaboration, Manufacturing, Industy 4.0.

1. Introduction

Historically, automation in industry has been kept separate from human workers for safety reasons, but Industry 4.0 aims to support the factory of the future, increasing effectivity and satisfaction [1,2,3] and recent development in collaborative robotics are leading to robots being incorporated into assembly lines in close proximity to human workers, sharing workspace and tasks. However, introducing human-robot collaboration (HRC) into assembly lines is complicated. For this, theoretically grounded tools are required to help assembly line designers better understand the requirements of both the human and the robot in multiple scenarios. A first step in that direction is to provide a tool for designers to build useful mental models of collaboration when it comes to HRC. Such tools exist for automation, notably *levels of automation* (LoA) [4,5]. LoA exist for e.g. self-driving vehicles [6]. Collaboration with automation does not fit easily into the existing levels of automation, as the focus is on achieving full automation, while in HRC the goal is that the human and the robot each perform the parts of the task that they are good at, thus complementing one another [7]. We therefore suggests *levels of collaboration* (LoC) that are built in a parallel fashion, instead of the linear construction of existing levels of automation.

2. Background

Industry 4.0 is a term for an approach to create the next generation of manufacturing [1,2] and advocates the use of sensors, ICT, and advanced automation throughout manufacturing facilities. The goal is to usher in the creation of "the factory of the future" [1,2]. Many tools are required to support the creation of the factory of the future, and work is ongoing to identify and answer the myriad challenges facing engineers and designers [1,2]. Today's industrial robots are contained within safety cells, being kept away from human workers for safety reasons. They are installed in a fixed manner, and reconfiguration is both costly and time-consuming. Projects, such as the Horizon 2020 project Manuwork, exist to explore the feasibility of flexible automation that can be added or removed from a manufacturing line, with the automation further supporting workers in their assembly through cooperation and collaboration.

2.1. Automation, human-robot cooperation, and collaboration

Cooperation between humans and robots has been discussed from many perspectives, and HRC can thus mean many things. To address this, it is necessary to keep in mind the intended context, and specify three things; which humans are involved, what kind of robots, and what kind of collaboration. Within the manufacturing domain and Industry 4.0, the relevant humans to consider are the people working alongside the machines, however, Industry 4.0 points out that other staff on the assembly line can approach and work with the robots. As for the robots it is more relevant to define them in terms of how humans perceive them than in terms of their actual capabilities. The actual capabilities can be derived from the particulars of the task, such as requirements in dexterity or strength, but safety issues are also important and common reasons for the specific properties of the used robots [8]. Collaboration also has many meanings and interpretations. From a cognitive systems perspective, collaboration has a more specific meaning than cooperation, which is more of an umbrella term for interacting agents. To collaborate in this sense is to partake in joint cooperative action or, in other words, shared cooperative activity [9]. For this to be possible, the involved agents need to have joint action, shared intentions, shared goals, and joint attention, each of which is a complicated phenomenon to handle in their own right. Joint action, for example, demands mutual responsiveness, commitment to the joint activity and commitment to mutual support [10].

The International Organization for Standardization (ISO) has defined collaborative operation as a “state in which a purposely designed robot system and an operator work within a collaborative workspace”, which in turn is a “space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation” [11]. These definitions are specifically made for HRC in the industry, and from this the definition of collaboration can be inferred to be a kind of work performed *simultaneously* and *co-located* by a robot and an operator during production. An important phrase to highlight is “purposely designed robot system”; reminding that design decisions need to be informed.

One specific aspect that can make or break interactions is trust, which is central also for interaction with automated systems [12]. Among the many ways of defining trust is “the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability” (p. 51, [12]). Worth noting is that trust should not be maximised. When overtrust occurs, where the operator's trust in the system exceeds its capabilities, the operator is inclined to delegate inappropriate tasks for the robot. On the other hand, if the operator does not trust the robot enough the robot will not be used to its fullest potential.

2.2. From Levels of Automation to Levels of Cooperation

Supporting joint action requires an understanding of aspects of collaboration and cooperation. This has led to domain specific definitions of various aspects of collaboration/cooperation, in some cases in the form of *levels of automation* (e.g. [6, 13]). Krüger, Wiebel, and Wersing [7] examine how the task responsibility is distributed through different levels of human-machine interaction, visually illustrating how the changes in the distribution of task responsibility does not simply involve handing off a task between the human and the machine, but rather that there is a degree of mixing of the task responsibility, with possible lack of clarity as to who is responsible for a particular operation within the shared activity.

The SAE levels of automated driving [6] are a well-known example of domain specific levels of automation, and are interesting as these levels range from complete human control of a vehicle, to fully autonomous operation in all conditions. An interesting attribute of these levels of automation is that they are portrayed as a single dimension, i.e. how much of the work is performed by each of the two envisioned partners in the activity (the human driver and the vehicle). The levels of Sheridan and Verplank [13] are similar in that they go from the activity being completely controlled by the human worker to being completely performed by the automation, with the automation determining what information needs to be communicated. What these levels of automation have in common is a presented one dimensionality, they do not explicitly support viewing collaboration, examining trust in the automation, or inspecting other elements of joint action such as whether the task or space are shared or separate, with collaboration placing higher requirements on both partners than cooperation.

Trust has, as mentioned above, been shown to be a critical factor in working with collaborative robots, as is having an understanding of both the task to be performed and the workspace in which the task is to be performed. From this it becomes clear that a way of understanding levels of automation specific to collaboration that can assist decision makers or designers of manufacturing lines in considering relevant factors would be useful, and this is what will now be shown.

3. Visualising Collaboration

Levels of collaboration (LoC) for industrial robots have been explored before, e.g. by Shi, Jimmerson, Pearson, and Menassa [14] who looked at low, medium, and high LoC in both a current state of industry and in a future state. Shi et al. [14] mostly focus on the technological aspects of collaboration, i.e. the limitations of then current automation, explaining that in a high LoC in the future state the robot is active, and in automatic mode. This is taken as a given now; collaboration with an inactive robot is not particularly useful. Shi et al. [14] also mention that the goal of collaborative robots in manufacturing is for a human worker and robot to perform tasks together, and that this is challenging. All the collaboration explored here happens at what Shi et al. [14] refer to as a High level of human-robot collaboration.

Each of the levels of automation that have been introduced shows each of the collaborators (the human and the automation) performing the task by themselves at the extremes of the scale, with the middle of the scale requiring some work from both partners. That middle section represents a problem for the automation, as these levels tend to denote an area wherein the automation is not always capable of completing the task, even though full autonomy is the state for which these systems strive. An example of this is seen in the SAE levels of automation for self-driving vehicles, where the description for the middle levels explain that the automation may need to disengage and the human may need to take over in certain circumstances [6].

Flemisch et al. [15] view this way of showing levels of automation along a scale from fully human controlled to fully automated as limited, and instead propose a spectrum of automation that takes into account more factors. That spectrum [15] includes more factors, but still uses one-dimensional visualisations to highlight certain aspects. This is useful for practitioners, as simpler visualisations can be designed to focus on one aspect at a time.

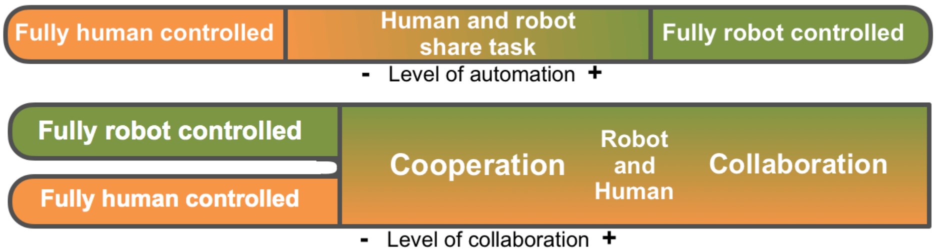

Figure 1. Top: the common view of LoA, going from full human control to full automation, with an area in the middle where the automation is not sufficient to complete the task (e.g. [6]). Bottom: Levels of Collaboration (LoC) as a parallel process that builds from a task being completed either by only a human or only by automation at the left, towards full collaboration at the right.

When aiming for collaboration the argument needs to be slightly different to when the goal is merely to view how much automation is involved. There is still a need for showing how much work each partner needs to contribute, but also a need for examining the depth and complexity of the collaboration between the partners. This is why instead of a scale from one extreme (human only) to another (automation only) we propose the use of a visualisation where the *level of collaboration* (LoC) becomes the main (horizontal) axis, with "human only" and "automation only" being placed on one side of the scale, gradually intertwining towards the other side of the scale. This can be seen in the lower visualisation in figure 1, where the levels go from describing a task fully performed by either a human or robot, goes to cooperation where both the human and robot may contribute to the task in some way, and finally full collaboration where the task responsibility is fully shared by both partners (see [7]).

How the scale is visualised affects what is prioritised by the user, which is why the LoC needs to be in focus. This is the primary difference between the LoC being developed here and the various different LoA that have been introduced, the focus is on *collaboration*, not on *degree/level of automation* and the highest level should involve full collaboration where the task space and task responsibility are shared equally between human and automation.

The requirements of each of the collaboration partners can then be highlighted, with the distribution of task responsibility being interpreted as increasing and mixing along the scale. The distribution of task responsibility was visualised by Krüger et al. [7] illustrating how the task responsibility of the human and the robot mix with increased collaboration. This serves as a reminder that a clear task separation or responsibility is not always possible (or even desirable) as in the case of one partner holding an object and the other partner guiding and fastening the object to other objects.

Indeed, as well as the simple LoA previously described going from fully manual to fully automatic, LoA have also been described in terms of a parallel control continuum [16]. This is useful when the focus does not lie on how much automation there is, but rather on the collaboration between manual work and automation.

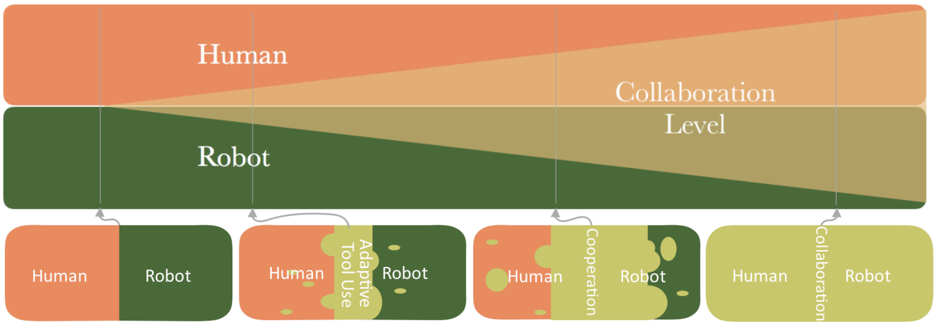

Figure 2. Visualisation of collaboration level. Lower image is adapted and modified from Krüger, et al. [7] to fit with the main visualization, showing collaboration as uniting the effort of the human and the robot.

Viewing the LoA as a parallel control continuum makes it simple to view the distribution of work as not going from fully human control to fully automatic control with some sort of problematic "in-between" state, but rather that both the fully human control and the fully automatic control build towards a "fully collaborative" state, see figure 1. This difference between the LoC visualisation and the LoA lifts the difference into focus; when it comes to HRC the goal can be to have the automation assume full control and the human to take over when needed, but when it comes to collaborating on a task, such as in a factory, then the goal is to use the best aspects of the human and the robot together, not to have automation take over the task.

Figure 2 shows how the parallel concept of LoC can be visualised, combining the concept shown in figure 1 with elements from the figures developed by Krüger et al. [7]. In here, those visualisations [7] are imagined as "slices" (or into the third dimension) of the parallel concept, and show how cooperation and collaboration gradually start between the human and the robot, and then gradually take over to become a full collaboration between human and robot. The visualisations made by Krüger et al. [7] used two colours, one for each partner in the collaboration, and showed how those gradually interleave. We add a third colour (see figure 2), which denotes the collaboration itself, suggesting that the collaboration itself can be viewed as an emergent property of the sharing of task responsibility.

4. Contribution

This short paper seeks to introduce a more practical way to think about levels of automation when it comes to HRC, focusing on *collaboration* rather than *automation* when, and only when appropriate, i.e. when the goal of the use of automation in that context is collaboration. The goal of the collaboration levels is to provide a framework into which legal, technical, and psychological requirements and limitations of both the human and the robot can be inserted. No claim is made that this is complete, but rather that the framework combines useful research in a way that supports future work on collaborative robotics in industry.

We have presented a way of visualising different situations where humans and robots work together. Contrary to many others, we have not framed it as a linear scale along which one agent is in control at each extreme. Instead we have used the degree of involvement in a common task as the distinguishing feature, and in doing so emphasised the various kinds of cooperation. Under the right circumstances, collaboration could emerge among cooperating agents, and change the nature of the interaction. It is thus important to consider collaboration from a holistic perspective, where it is something fundamentally more than two individual agents working.

Future work requires clearly defining LoC to operationalize the functionally different cooperation stages is a next step, after which a tool, such as a checklist, would directly benefit practitioners such as assembly line designers in industry.

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