WHEN IS A ROBOT A COBOT? MOVING BEYOND MANUFACTURING AND ARM-BASED COBOT MANIPULATORS

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ABSTRACT

Collaborative robots ("cobots") have attracted growing attention in academia and industry over the last years. Due to in-built safety features and easy programming, they allow for close human-cobot collaboration and support e.g. flexible manufacturing. However, the lack of a common understanding what a cobot is along with its traditional focus on arm-based cobots complicates further research and industry adoption. Thus, this paper analyses the variety of definitions in literature incl. standards and practice examples to derive a consistent and holistic definition and taxonomy of what a collaborative robot is. Aside from contributing a structured overview of various forms of human-robot collaboration, this builds an important foundation for future research as it systematically differentiates different cobot types. Companies and other organisations will benefit by a better understanding of what type of cobot they need and how to ensure safe collaboration.

Keywords: Technology, Design engineering, Industry 4.0, Collaborative Robotic

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1 INTRODUCTION

Companies are confronted with an increasing need for flexible product development processes due to providing more customer-specific products or reacting to changing technologies and markets (Lasi et al., 2014). In addition, recent trends indicate a desire to re-shore R&D and manufacturing as a reaction to global supply-chain disruptions due to Covid-19 and political instabilities (Hohenstein, 2022). Re-shoring requires high underlying flexibility to manufacture customised products and small batch sizes (Dachs et al., 2019). While automatised manufacturing systems are usually too rigid for frequently changing products, manual tasks are often tiring, repetitive and sometimes even potentially dangerous (Djuric et al., 2016) like welding in confined spaces or lifting heavy objects. A shortage of skilled workers across various sectors, such as manufacturing, health care, and hospitality, further complicates re-shoring ambitions, especially for small and medium-sized enterprises (SMEs) (Dachs et al., 2019).
One technology that enables flexible processes is the collaborative robot, a so-called cobot. Unlike conventional industrial robots, cobots are designed to safely operate in a shared workspace with humans, taking on repetitive, dull, and tiring tasks (Djuric et al., 2016; ISO 10218-2:2011). Cobots are an attractive proposition for SMEs as they lower the barriers for leveraging automation. Many cobots are designed to be user-friendly and can be programmed by direct physical interaction, meaning they can be commissioned by existing staff with minimal training. The "safe" nature of cobots means that cobot systems can be used without the need for expensive and time-consuming safeguards. This facilitates the agile utilisation of cobots, which is important for SMEs that typically produce many variations of products in smaller production runs. Furthermore, cobots have lower costs than conventional industrial robots (Kopp et al., 2021).
However, to achieve these benefits, cobots must interact safely with operators and other humans in their environment. While cobot standards focus on (arm-based) cobot manipulators with defined safety modes (EN ISO 10218-1:2011), these modes are necessary but not sufficient to ensure safety (Djuric et al., 2016; Vysocky and Novak, 2016). Moreover, the focus on cobot manipulators falls short of covering the increasing variety of robots that work collaboratively with humans in the context of seamless physical human-robot interaction (pHRI) (Haddadin and Croft, 2016). Research continues to push the boundaries of cobots, such as by enhancing industrial robots to act as high-payload cobots, or by implementing service robots in logistics, households, restaurants or the health sector that need to work closely and safely with humans but are not covered by current cobot standards.
As the characteristics of cobots are significantly different from those of traditional robots and other machines (ISO/TS 15066:2016, 2016), a conceptualisation of collaborative robots is crucial to identify suitable applications and tasks as well as the health and safety implications in industrial settings (Vicentini, 2020). Especially in practice, it can be ambiguous what differentiates a cobot from a robot. These ambiguities can lead to possible danger due to incorrect assumptions being made about safety, along with general cobot performance. Thus, the resulting question is: *Which characteristics differentiate a cobot from a robot?*
This paper addresses the ambiguity between robots and cobots by conceptualising cobots, i.e. developing a definition and taxonomy of cobots that capture the large variety of robots collaborating with humans. A clearer understanding of when a robot is used in a collaborative way supports systematic development and safe use of cobots. To do so, this study uses a literature analysis of robot and cobot definitions along with semi-structured interviews. The remainder of the paper covers research design in section 2 and insights from the literature analysis in section 3, complemented by interview findings in section 4. Section 5 includes the synthesis of a definition and taxonomy of cobots while section 6 concludes the study by discussing the implications and an providing an outlook on further research.

2 RESEARCH DESIGN

A mixed-method research design was used for this study. In the first step, a literature analysis identified established definitions of robots and cobots, such as from the renowned "Springer Handbook of Robotics" (Siciliano and Khatib, 2016). In addition, frameworks and classification schemes were analysed, structuring different types of cobots and human-robot interaction. In parallel, different use cases of cobots and human-robot interaction were identified. Aside from scientific literature, industry reports and company websites were included as well to cover an industrial practice perspective.

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In the second step, a series of interviews were conducted to validate literature findings and explore the understanding of industry and research experts concerning the characteristics and features of a cobot. The semi-structured interviews took place between August and October 2021 as part of the research project "The Impact of Robotics on Work Health and Safety" (see Acknowledgements). The goal of the interviews was to cover a broad range of perspectives from different domains and steps of the cobot value chain. Based on an internet search of organisations manufacturing, selling, and potentially using cobots, as well as recommendations of known cobot experts and users (i.e. snowballing), 41 individuals from 28 organisations in Australia were identified as potential research participants and contacted via phone calls and email. Of those, 15 people agreed to participate in one-hour individual online in-depth interviews (Table 1). The semi-structured interviews included questions around their understanding of cobots, and the drivers for and use of cobots. The definitions, use cases and interview insights formed the bases for developing a cobot definition and taxonomy through iterative evaluation and refinement.

Table 1. List of interviewees (15 interviews, multiple roles per interviewee possible)

Roles (interviewee count)	**Description**
Manufacturers (3x)	Companies responsible for the design and manufacturing of the cobot.
Distributors (4x)	Companies that are authorised by manufacturers to stock and provide some implementation support for specific cobot brands.
Suppliers (3x)	Companies that sell cobots and provide some implementation support.
Integrators (2x)	Companies that assist users to integrate cobots into workplaces and configure software and hardware systems.
Cobot users (5x)	Companies or individuals that have purchased and use cobots.
Potential cobot users (1x)	Companies or individuals interested in purchasing cobots in the future.
Practice partners (3x)	Individuals who are associated in the development of the cobot industry, including academic researchers.

3 LITERATURE REVIEW

3.1 Definitions of robots

As cobots are a special type of robots, it is important to briefly discuss the definition and variety of robots before focusing on cobots. The term "robot" is attributed to the Czech writer Karel Čapek and his brother Josef Čapek, who derived it from the Czech word "robota", i.e. "forced labour" (Merriam-Webster, 2022). According to Merriam-Webster (2022), a robot is "*a machine that resembles a living creature in being capable of moving independently (as by walking or rolling on wheels) and performing complex actions (such as grasping and moving objects)*". This reference to a living creature is rather noteworthy, while the aspects can also be found in definitions like: "*A robot is an autonomous machine capable of sensing its environment, carrying out computations to make decisions, and performing actions in the real world.*", which stresses the autonomous and real-world aspect of performed actions (Guizzo, 2018). In contrast, the definition of Cambridge Dictionary (2022) is more focused on how it is "*a machine controlled by a computer that is used to perform jobs automatically*". This broad definition is also reflected in the vast variety of existing robot types and application areas, which are often in shared human-machine environments, such as aerospace (e.g. autonomous drones), consumer (e.g. vacuuming, assistance), disaster response (e.g. inspections, search & rescue), education, entertainment (e.g. show or comedy bots), exoskeletons (e.g. rehabilitation, strength support), humanoids (e.g. social interaction), medical (e.g. surgery support, bionic prostheses), military & security (e.g. surveillance, bomb disposals), telepresence (e.g. robot avatar), and service robots (hospitality) (EN ISO 10218-1:2011; Guizzo, 2018).

An industrial robot is a particular type of robot that is defined as an "*automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications*" (EN ISO 10218-1:2011). Aside from their focus on industrial, i.e. production-oriented use cases, a key unique feature is that they are considered to be an incomplete machine. They are only complete when combined with an end-effector or end-of-arm-tooling, such as a gripper or welding torch (Mueller et al., 2016; Schunkert and Ryll, 2022). This allows industrial robots to achieve multiple purposes in contrast to other robots that focus on a defined task (e.g. a vacuum robot).

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3.2 Definitions of cobots

Colgate et al. (1996) present what is widely considered the first definition of a cobot: "*A "cobot" is a robotic device which manipulates objects in collaboration with a human operator*", and they gave an example of a unicycle cobot with a steerable wheel. In this early iteration, the cobot itself is understood to be "*intrinsically passive*", i.e. it is guided by a human, but it constraints where the human is allowed to move the cobot. This aligns with subsequent definitions like "*Collaborative robots "cobots" are intended for direct interaction with a human worker,* **handling a shared payload**", which still uses a cobot to "*constrain and guide the motion of the shared payload, but add little or no power*" (Peshkin and Colgate, 1999).

However, in contrast to this, current understanding and definitions are that cobots emerged as a special type of industrial robots, having multiple degrees of freedom (typically 6 axes) and supporting manufacturing-related tasks (Djuric et al., 2016). Examples include: "*Cobots are* **industrial robots** *specially designed to work in close contact with people*" (European Commission, 2018). In comparison to industrial robots, cobots are easier to program/teach, more flexibly usable and focus on ensuring safe interaction with humans in a collaborative workspace, i.e. an "*operating space where the robot system (including the work piece) and a human can perform tasks concurrently during production operation*" (BS 8611:2016; EN ISO 10218-1:2011; ISO 10218-2:2011). This allows the combination of robotic endurance and strength with human cognition and creativity (Djuric et al., 2016) to perform collaborative operations, i.e. "*state[s] in which purposely designed robots work in direct cooperation with a human within a defined workspace*" (EN ISO 10218-1:2011). Here, "*operators can work in close proximity to a robot system while power to the robot's actuators is available, and physical contact between an operator and the robot system can occur within a collaborative workspace*" (ISO/TS 15066:2016). To enable this, cobots are required to have at least one of the following four safety modes (EN ISO 10218-1:2011):

- **Safety-rated monitored step:** A cobot recognises when humans are in its direct proximity and stops all movements to avoid hazardous collisions.
- **Hand guiding:** The cobot can be hand guided by a user to perform specific tasks or to be programmed. It recognises user input and stops automatically when contact with the user is lost.
- **Speed and separation monitoring:** The cobot workplace has defined areas, e.g., if a user is in a safe, so-called "green area", the cobot can run at full speed. However, if a user enters an area with elevated risk, such as a so-called "yellow area", then speed should be reduced, and in a dangerous "red area", speed might be further reduced or the specific movements may be blocked.
- **Power and force limiting:** By limiting the power and force of a cobot, injuries can be reduced in the case of a collision. This can also include the use of flexible instead of stiff joints, such as elastic actuators with a spring between the gearbox and the joint.

Recent definitions seem to broaden and go beyond (arm-based) cobot manipulators, such as "*any robot operating alongside humans without the presence of a fence is a collaborative robot*" (Adriaensen et al., 2022), but still tend to focus on industrial / manufacturing applications. This recent broadening of the standard word definition means that some of the expected safeguards that are notionally expected by the decade-old ISO 10218-1 standard may no longer be applicable, or relevant. By varying the definition of the word "cobot", and weakening or confusing the safety expectations, this impacts on the safety of an ever-increasing user base.

3.3 Categorising human-robot collaboration

Aside from the four cobot safety modes (EN ISO 10218-1:2011), robots are considered collaborative when they: (a) share the **same workspace** with a human, and (b) perform their tasks **at the same time** as a human, which can require physical contact between a robot and human – otherwise, they are seen as industrial robots (Mueller et al., 2016; Vicentini, 2020). Enhancing the idea of safety modes and shared space and tasks, Kopp et al. (2021) present a framework with four types of human-robot interaction in manufacturing (Figure 1). Ranging from a fenced-off cell to full collaboration, it also characterises each interaction type with respect to the interconnectivity of tasks, physical contact and robot speed. While this classification is highly valuable, the framework focuses on manufacturing-related cobot manipulators.

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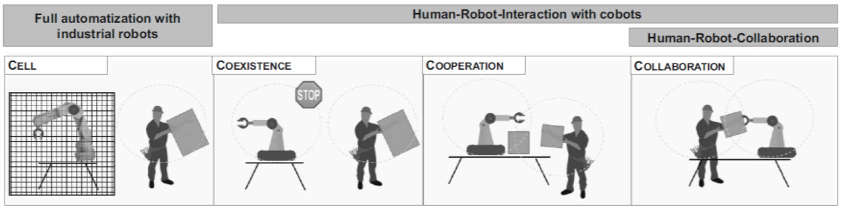

Working steps	Sequential			Simultaneously
Working space	Separated working spaces		Shared collaboration space If synchronised: Timely separated	
Working tasks	Tasks are not linked		Linked tasks	Shared tasks
Physical contact	Impossible		Possible, not necessary	Possible, often desired
Minimal safety requirements according to DIN EN ISO 10218-1	Automatic operation with safeguards	Safety-rated monitored stop	Speed and separation monitoring Power and force limiting	Hand-guided control
Robot speed	Maximum speed	Limited speed		

Figure 1. Four types of human-robot interaction in manufacturing (Kopp et al., 2021)

Figure 1 focuses on industrial robots and cobot manipulators. Acknowledging the growing diversity of collaborative robots beyond manufacturing settings, Haddadin and Croft (2016) classify cobots, or more broadly, physical human-robot interaction, along two dimensions: (1) level of proximity of human and robot, and (2) level of agency, i.e. autonomy of the robot and its actions. While proximity aligns with the collaboration perspective used by Kopp et al. (2021), the agency/autonomy aspect is an important extension to differentiate different types of collaboration. However, through its exclusive focus on cobots, it does not allow differentiating cobots from robots.

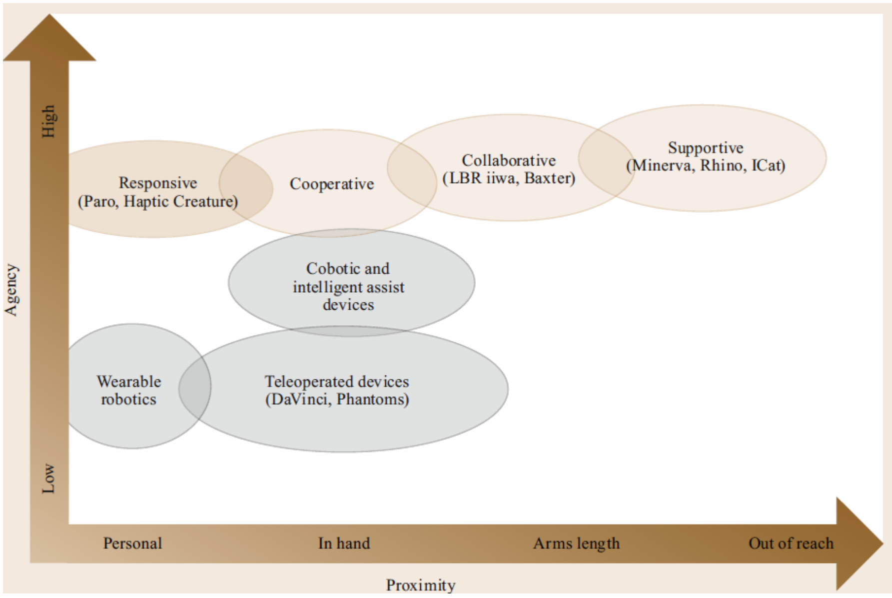

Figure 2. Classification of physical human-robot interaction (Haddadin and Croft, 2016)

3.4 Examples of human-robot interaction and collaboration

The most prominent area of application of cobots is still manufacturing and logistics, with a large variety of use cases, ranging from assembly and pick-and-place tasks, to sanding and finishing, welding, quality inspection, and machine tending (Buchert, 2021; Marr, 2022). This includes cobot manipulators mounted on an autonomous mobile platform, which can move the manipulators' base around (Vysocky and Novak, 2016). However, there is a growing variety of human-robot collaboration examples that are outside of a factory-based manufacturing setting, such as:

- **Agriculture:** e.g. the autonomous harvesting transport robot "Burro" (https://burro.ai) or the milking robot "Lely Astronaut" (https://www.lely.com/au/solutions/milking)
- **Construction and maintenance: e.g. sandblasting cobot "ANBOT" (**Carmichael et al., 2019**)**
- **Food and beverage preparation:** e.g. the cooking robots "Moley" (https://moley.com) and "Flippy 2" (https://misorobotics.com)
- **Service robots** (Wirtz et al., 2018): e.g. serving robots like "botHUB" (https://bothub.com.au)

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- **Social interaction:** e.g. companionship and social interaction trainer "iCat" (https://www.hitech-projects.com/icat, therapeutic robot "PARO" (www.parorobots.com), and the information provision, guidance and companionship robot "Pepper" (http://us.softbankrobotics.com/pepper)
- **Healthcare:** e.g. the hospital patient care teams support robot "Moxi" (https://www.diligentrobots.com), the massage robot "Alex" (https://www.massagerobotics.com); surgery robot "Da Vinci" (https://www.davincisurgery.com/da-vinci-systems).
- **Wearable cobotics** (Haddadin and Croft, 2016), e.g. exoskeletons. Ekso Bionics upper and lower limb exoskeletons for healthcare and industrial tasks (https://eksobionics.com). Ottobock exoskeletons for materials handling and other industrial tasks (https://ottobockexoskeletons.com/).
- **Household robots:** e.g. mopping/vacuum robots like "Roomba" (https://www.irobot.com.au). Lawn mowing robots such as Husqvarna's "Automower" (https://www.husqvarna.com/us/discover/robotic-mowers/about/).
- **Mobile multi-purpose robots:** e.g. BostonDynamics "Spot" (https://www.bostondynamics.com), which can be used for scenarios like disaster management, or guard-bots like Justus security robots.

4 INTERVIEW FINDINGS

The interviews revealed a general confusion about what a cobot is and how cobot applications can be set up safely. Despite the goal to cover a broad range of human-robot collaborations, interviewees mainly worked with cobot manipulators in a manufacturing setting.

4.1 Safety: the often-misunderstood key for cobots

In line with the literature, safety was stated to be a key consideration when buying and using cobots. However, interviews revealed a common misperception of cobots always being inherently safe, which often results in less prioritisation of work health and safety evaluations. Marketing slogans have incorrectly led some intelligent people to wrongly assuming that a cobot might be appropriate and safe for any application – as evidenced by a response from a senior manager interested in buying a cobot: "*you don't have to worry about the risks with cobots*". However, this conflicts with what a cobot supplier stated: "*I can go and sell a collaborative robot but it doesn't mean that the application is collaborative*". Thus, despite their safety features, the actual safety of a cobot depends on several different aspects, which are addressed in the following sections.

4.2 Ambiguous usage of the term cobot

An identified key issue was that users implemented cobot equipment for inappropriate applications. This issue was caused by unclear definitional boundaries and use cases between cobots and industrial robots. Respondents often used the terms 'robot' and 'cobot' interchangeably to describe human-robot collaboration. If left unclear, end users may (a) use their cobots for non-collaborative applications or (b) misuse industrial robots for collaborative scenarios. In (a) the consequences are not dire and will likely just result in reduced productivity; however, in (b), there is the potential for serious hazards.

4.3 Cobots for non-collaborative applications

On the one hand, interviews highlighted that the term collaboration could be vague and interpreted in various ways. Most interviewees said that they did not use their cobots for collaborative applications. Instead, they used them for coexistent or cooperative applications. Interviewees explained that this was often due to the main selling point of cobots being cheaper, easier to use – often as "plug & play" – and taking up less factory floor space in the case of manufacturing scenarios. This enables workers to safely work alongside automated processes. A safety peripheral manufacturer that converts industrial robots for collaborative use explained that for many of their clients, the desire to purchase their equipment was so that they could go fenceless. They explained that fences were "*a hindrance to good flow through*".

Although these additional safety features compared to an industrial robot do not cause direct problems, these safety features usually come with reduced movement speeds and payloads. When a cobot was observed to approach its maximum payload, interviewees reported that the cobot's performance becoming inconsistent and unreliable – "[they] *jitter a little bit*, *as if it's moving on its own and it gets really slow*" (integrator interviewee). When cobots are a part of a larger, more complex socio-system, this unreliable performance can impact entire work systems and processes.

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4.4 Industrial robots for collaborative applications

On the other hand, interviewees also reported a strong interest and business case for repurposing industrial robots into something collaborative – especially for small and medium-sized enterprises. Aside from increased flexibility, a key driver is to overcome the traditional speed and payload limitations of a cobot. This is reflected in a statement made by an interviewed cobot researcher: "*We're trying to think of cobots as robots that can work closely with people and in fact they don't need to be this so called cobots that people are selling as cobots. We think some cobots may be much bigger robots, we've got a 200 kg payload robot here that we want to be a cobots in some situations. Because it's about how it performs, not about some arbitrary label […] Then there's no reason why it also can't be a cobot."*. This desire is reflected by several leading cobot manufacturers recently announcing new cobots in their line-up with larger payload capacities, such as the UR20 from Universal Robots (https://www.universal-robots.com/products/ur20-robot/) and the TM20 from Omron (https://industrial.omron.eu/en/products/collaborative-robots).

In addition to external sensors, the repurposing of industrial robots as cobots can be realised by technical add-ons as an integrator stated: *"I do know of some products that can be installed on industrial robots that make them behave like cobots. I think they're called Airskin […]. Where if the capacitive pads make contact with the human, they basically stop instantly[…]"*. For reference, Airskin is a modular, add-on safety peripheral to enable human robot collaboration for industrial robots (https://www.airskin.io).

However, aside from distributors and integrators stressing the importance of reduced speeds to reduce the likeliness and impact of collisions, industrial robots usually lack the functionality to adequately run safety detection programs and react in a timely manner. This can cause a serious risk as expressed by an integrator: *"… [an industrial robot] doesn't stop in a safe manner. I've seen robots collide with conveyors and basically bend them. And then it will stop."*

4.5 The specific application differentiates a cobot from a robot

Aligning with the statement of an integrator ("*I can go and sell a collaborative robot but it doesn't mean that the application is collaborative"*), the main driver for non-collaborative applications was not the cobot itself but the task assigned to a cobot and the end-effector. A common example of how end-effectors can jeopardise inbuilt cobot safety features and thus their ability for collaborative operations is the use of sharp end-effectors, which can circumvent force limitations, that assume a much larger surface area of interaction. An open blade in any workplace remains dangerous even if a cobot is turned off. This reveals an emerging misunderstanding in what exactly is 'safe' about cobots. A cobot user responsible for cobot training summarised: "*It isn't a collaborative robot until we establish those basic kinds of safety and interactivity requirements that warrant it to be a robot that we can interact with*".

A root cause of this jeopardised safety is that cobot manipulators are designed and sold as so-called part machines, which means that the base cobot is incomplete and requires additional end-effectors or tools to perform a specific task (Mueller et al., 2016). Suppliers and manufacturers can only assure that specific parts are safe but cannot prevent users from combining them with unsafe parts. Traditionally, integrators had a duty of care to install complete robot systems that adhere to local standards and holistically assess the task application. However, cobot users are not required to consult with integrators to buy a cobot or to change the application, task or end-effectors. Especially, plug&play features seem to invite such unsafe combinations. Thus, the safety and collaboration ability of a robot always needs to be assessed holistically when setting up the system and when changing it.

4.6 Cobot appearance and interaction modes are crucial for a socio-technical system

Due to their close interaction with humans, cobots are no longer purely technical systems. Interviewees reported that cobot appearance and behaviour can make operators feel uncomfortable. For instance, a force impedance mode can make cobots feel more "*squishy and playful*" to users. While this more playful interactivity enables the cobot to be marketed as friendlier, it does result in less precise manufacturing outcomes. A cobot user explained that in this mode cobots become more responsive to the physical touch of operators, which could make them begin to empathise with the cobot. They claimed that this response to their physical touch immediately made "*the interaction more intimate because you care more…like it's like a little puppy rather than a rigid arm*". However, the cobot user was concerned that there may be inadvertent and unnecessary psychological burdens on operators that could be brought on by caring for an anthropomorphic object – such as in the case of a collision or replacement.

Another social aspect addressed the anticipated behaviour of a cobot. Users tend to expect a cobot to move in a predictable human-like manner or behave with "*common sense*". However, based on the specific situation and programming, cobots can make unexpected movements, which can cause physical injuries or mental stress. This is exemplified when cobots are not stationary, such as where cobot manipulators are mounted on mobile platforms like automated guided vehicles (AGV), or a mobile service robot. In dynamically changing environments, such as factory floors, hospital hallways, restaurants or public spaces, cobots regularly face the risk of colliding with people who pass through the same space but might not be trained cobot users. Interviewees stressed the need to provide people training to become 'digitally-enabled', ideally in combination with building learning cultures to support the safe and sustainable growth of cobot integration.

5 CONCEPTUALISING COLLABORATIVE ROBOTS

5.1 Definition of collaborative robots

The literature review revealed common characteristics of cobots like the close and direct contact between robots and humans along with purposeful collaboration (European Commission, 2018; ISO/TS 15066:2016, 2016; Peshkin and Colgate, 1999). Those can be combined with general robot aspects, such as being a machine that cautiously performs complex tasks in the real world (Cambridge Dictionary, 2022; Merriam-Webster, 2022) enabled through its own sensing and decision-making (Guizzo, 2018). This focus on the real world implies a focus on physical cobots and excludes purely virtual machines like chatbots. Definitions can change over time, which triggers their re-evaluation and update. The interviews highlighted that a cobot's ability to collaborate with humans depends on its specific technical, organisational and social settings. These considerations are synthesised into the following definitions:

*A **collaborative robot (cobot)** is a robot that can interact safely in close spatial and temporal proximity with humans on shared tasks - enabled through environment sensing and autonomous decision making.*
*A **cobot system** comprises a cobot, an application, (additional) safety equipment, and an end-effector if applicable.*
*A **cobot workplace** combines a cobot system with humans in different roles, performing application-related processes, while being guided by ethical principles.*

5.2 A collaborative robot taxonomy

While it is crucial that the definition is broad to cover the variety of cobots, a more fine-grained structure is needed to identify different types of cobots with similar characteristics. This is important as the type of cobot determines principal behaviour, suitable applications and use cases, R&D direction, and work health and safety requirements and procedures.

Two independent main dimensions were identified based on the literature review and interviews: level of human-robot interaction and the level of autonomy (Table 2). The **level of interaction** (Kopp et al., 2021) is a key dimension as both interviews and cobot examples highlight a varying degree of human-cobot interaction. It also allows to clearly contrast cobots from physically separated robots, which supports building a better understanding of cobots. Human-cobot interaction requires technical, organisational and social safety features and mechanisms, which need to be regularly assessed since they can change over time. In general, this is a n:m type of interaction, i.e. one or more cobots can interact with one or more humans. The second key dimension is the **level of autonomy** (Haddadin and Croft, 2016). This ranges from passive and human-guided cobots that support humans in e.g., performing a movement properly, via active and human-guided cobots like an exoskeleton that provides force-torque support, semi-autonomous cobots that rely on frequent user input to perform a task, up to fully autonomous cobots. This also links to the required level of intelligence of a cobot. Additional dimensions which are closely embedded in the two key dimensions are the (a) **level of mobility**, i.e. stationary vs. mobile cobots; (b) **type of interaction**, i.e. tangible vs. intangible, such as guidance; (c) **type of application**, such as object manipulation, object transport, force/torque support, guidance, and communication; (d) **flexibility of application**, i.e. defined vs. regularly changing; and (e) **completeness of machine**, i.e. part vs. full machine.

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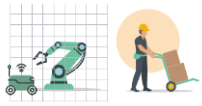
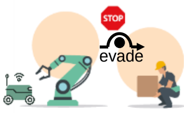
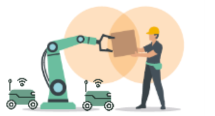
Table 2. Collaborative robot taxonomy with cobot examples

	Level of human-robot interaction			
Level of agency/ autonomy	**Physically separated**	**Coexistence**	**Cooperation**	**Collaboration**
				
	robot operates in separation from humans on separate tasks	robot stops or behaves evasive in shared spaces; separated tasks	cobot operates alongside humans on linked tasks but limited interaction	cobot collaborates (hand-in-hand) on shared task
	Separated space and time	→	→	Shared space and time
Fully autonomous	robot independently executes set task and reacts to issues, e.g. autonomous drones	autonomous robot working distanced from humans, e.g. autonomous forklifts, warehouse logistics; cleaning robots "Roomba"	autonomous robot working in close proximity of humans, e.g. autonomous farm cobot "Burro"	autonomous robot working in close contact with humans, e.g. patient care "Moxi"; "Pepper"
Semi-autonomous with user input	robot semi-autonomously executes a set task, with expected human input., e.g. tele-operation with transfer delays, Mars rover	robot semi-autonomously executes a given program, e.g. kitchen robots "Moley", "Flippy 2"	cobot semi-autonomously navigates and works in shared space, e.g. serving cobot "botHUB", cobotics surgery "Da Vinci"	cobot semi-autonomously operates in close proximity with humans, e.g. "iCat", "Lely Astronaut"
Active & human guided / programmed	robot is fully human controlled/ programmed, e.g. traditional offline-programmed manufacturing robot, simple teleoperation	robot is fully controlled by humans and operates in mainly unshared spaces, e.g. guard robots, "Justus security robot"	fully controlled cobot operates in shared space with humans, e.g. avatar cobots, telepresence robots.	fully controlled cobot operates in direct contact with a human, e.g. rehab. cobots; "ANBOT", Otto-bock exoskeletons;
Passive & human guided / programmed	passive robot constrains movement or operation of objects, e.g. advanced fail-safe	passive robot constrains movement or operation of objects, e.g. passive gripping robots to hold parts	passive cobot constrains movement or operation of objects in shared space, e.g. taking and holding objects	passive cobot directly constrains human movement, e.g. simple rehab. cobot, Colgate's cobot

(Icons use mobile robot icon from Flaticon.com made by Dooder)

6 IMPLICATIONS AND FUTURE RESEARCH

The growing popularity and diversity of collaborative robots (cobots) have led to ambiguity of what differentiates a cobot from a robot. This lack of clarity and understanding has a major impact on choosing an appropriate application for/with cobots, including work health and safety. This affects both, the use phase and the design and development phase of new cobots in terms of safe hardware, software, and AI features. This paper's contribution is twofold and supports the systematic research and development of new collaborative robots and the purposeful use of cobots to manufacture customised products and services. This study contributes to a clear and holistic definition of a collaborative robot that goes beyond arm-based cobots, including a taxonomy that allows for structuring the constantly growing variety of cobots and their use cases. Practitioners benefit from consolidated advice that ensures that cobot features are not jeopardised by inappropriate tools or use cases.

Although interviewees also came from international organisations and are active in international networks, the current interview focus on Australia could pose a potential bias. Thus, future research needs to broaden the scope and involve a broader and more international group. This also affects the need to discuss the new cobot definition and taxonomy with an international and interdisciplinary group of researchers and practitioners to fine-tune and ensure acceptance across communities.

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