

Towards the Safety of Human-in-the-Loop Robotics: Challenges and Opportunities for Safety Assurance of Robotic Co-Workers*

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Abstract—The success of the human-robot co-worker team in a flexible manufacturing environment where robots learn from demonstration heavily relies on the correct and safe operation of the robot. How this can be achieved is a challenge that requires addressing both technical as well as human-centric research questions. In this paper we discuss the state of the art in safety assurance, existing as well as emerging standards in this area, and the need for new approaches to safety assurance in the context of learning machines. We then focus on robotic learning from demonstration, the challenges these techniques pose to safety assurance and outline opportunities to integrate safety considerations into algorithms “by design”. Finally, from a human-centric perspective, we stipulate that, to achieve high levels of safety and ultimately trust, the robotic co-worker must meet the innate expectations of the humans it works with. It is our aim to stimulate a discussion focused on the safety aspects of human-in-the-loop robotics, and to foster multidisciplinary collaboration to address the research challenges identified.

I. INTRODUCTION

Robotic co-workers are machines designed to support flexible manufacturing in collaboration with humans. They complement the skills and cognitive abilities that enable humans to accomplish frequently changing, varied or imprecise tasks, with strength, precision, endurance and limitless capacity for repetition. These robots are expected to provide assistance for a wide variety of tasks. To reduce or even eliminate the effort involved with frequently re-programming robots so that they can perform new tasks, techniques that enable robot learning from demonstration are now being developed [1]. Such techniques empower non-experts to teach or train robots, e.g. how to be most useful within a flexible manufacturing environment.

Flexible manufacturing requires robotic co-workers to act within the personal space of a human. They may be involved in shared manipulation of objects and even make direct contact with their human operators. To be genuinely useful, some robots may need to be powerful and therefore are potentially dangerous. Safety of the humans who interact

with these machines is clearly a prime concern in these settings. The introduction of learning from demonstration techniques further emphasizes the need to ensure the safety of human operators, both during the learning phase and also afterwards, when the newly acquired task is being performed by the robot. The safe operation of the robotic co-workers is a core foundation for humans to establish trust in them.

In this paper we investigate issues surrounding safety assurance of robotic co-workers. We start from a technical, robot-centric angle by considering safety assurance and certification requirements currently under development for robots that work in direct interaction with humans in shared spaces. We show that there is a considerable gap to bridge, and hence a research challenge associated with safety assurance of robots that flexibly learn new tasks “on the fly”. We review proposals to shift parts of safety assurance from design time to runtime, and investigate the feasibility of using similar techniques to achieve safety assurance for robotic co-workers. We then focus on robot “learning from demonstration” techniques, in particular on reinforcement learning, and illustrate both the opportunities arising from humans in the loop, as well as the dangers and the associated responsibility to ensure the safety of the human operators. We aim to identify opportunities to integrate safety considerations into the design of robotic co-workers, i.e. into the embedded learning algorithms from the beginning “by design”.

Our discussion then takes a human-centric view and focuses on the psychological challenges associated with human-robot co-worker teams. We stipulate that, to achieve high levels of safety and ultimately trust, the robotic co-worker must meet the innate expectations of the humans it works with. For instance, if a co-worker robot were to be equipped with head and eyes, it would be expected to use eye gaze as warning signal in case of danger by directing gaze toward the source of danger. Also, in a shared activity, gaze would be expected to be directed to the task at hand in line with human expectations on the focus of attention. This requires deep understanding of the signals sent by humans and the way humans interpret these signals when observed in human co-workers.

With this position paper we aim to stimulate a discussion focused on safety aspects of robotic co-workers, both from a robot design as well as from a human-centric perspective. Our paper poses more research questions than it provides answers. These questions, however, are designed to open up an opportunity for the research community to address safety “by design”. This is both a timely as well as a necessary endeavour, because any techniques that are to be

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used in practice will need to be demonstrably safe, and, most importantly, will need to be accepted by humans, i.e. they need to gain the trust of the humans who work with them.

This paper is structured as follows. Section II is focused on safety assurance; it presents insights into existing and forthcoming standards covering the safety of robotic co-workers in an industrial setting. Section III investigates robotic learning from demonstration, and we identify opportunities and challenges to integrate safety “by design”. Section IV considers the psychological challenges associated with human-robot co-worker teams arising in flexible manufacturing scenarios. Finally, Section V summarizes and concludes.

II. ASSURANCE AS A FOUNDATION FOR TRUST

A. Existing and forthcoming standards for safety assurance

The success of a human-robot co-worker team heavily relies on the dependability of the robot. Dependability has been defined as “the ability to deliver a service that can *justifiably* be trusted” [2]. Dependability is an over-arching concept that includes attributes such as safety, availability, reliability, predictability, integrity and maintainability. Safety is a critical aspect of dependability, which traditionally is assured prior to a system’s deployment. Safety assurance assesses the absence of harmful consequences of a system’s actions (or in-action) on users and the environment.

A key property of dependability assurance is that it is a subjective condition of a system’s users as well as an objective property of the system itself. Even if a system design contains no flaws and its operation never causes harm throughout its life, if its users cannot be assured of this before they start to use the system, then they may not trust the system and thus may never use it. Therefore, the art of designing dependable systems is not only to create a flawless design, but to do so in a manner that permits such flawlessness to be demonstrated. This requires careful choices of a system’s architecture and mechanisms, because only those technologies whose correct operation can be easily verified and validated are suitable for such applications.

Until recently, the practical deployment of robotic assistants has been held back by the lack of credible standards and techniques for safety assurance. In traditional robotic applications, safety has been achieved by confining robots to closed workplaces from which humans are isolated. Safety is assured by demonstrating that the isolation is effective, rather than by demonstrating the safety of the technology of the robot; the former is usually a much easier problem to solve. Consequently, safety is not an essential aspect of such robots’ operations, and performance is the key objective.

Robotic co-workers, however, are designed to assist humans in their work within the same workplace. It is inherent to their purpose that they cannot be isolated from the people they are intended to assist. Collaborative operation, however, in particular in a shared space, is a much more complex problem to assure and requires more extensive assessment of the technology of a robot and its surroundings than was necessary in more traditional applications.

Robots are expected to be safety-certified when entering the market, which provides assurance that deploying a system does not pose an unacceptable risk of adverse consequences. Industry standards for collaborative operation in robots are currently the focus of extensive study in the major international standards agencies. The Technical Committee (TC) 184, Sub-Committee (SC) 2 of the International Standards Organization (ISO) develops standards for robots and robotic devices, and currently has working groups covering industrial, medical, and service robots. Working Group (WG) 7 has developed the ISO 13482 safety requirements standard for service robots, including physical assistance and mobile servant applications, and WG3 of the same committee is developing a Technical Specification (TS) 15066 focused on collaborative robots. TS 15066 provides guidance on collaborative operation for industrial applications, including the specification of several collaborative modes of operation and their associated safety requirements.

Central to the guidelines in TS 15066 are hazard identification and risk assessment. Both are performed by experts and are specific to the collaborative task shared between a robot and its human operator. Thus, task identification is key to the correct determination of any foreseeable hazards. Risk assessment is then performed on these hazards, including the identification of values such as the maximum allowable speed of movement for the robot and the minimum separation distance between robot and human, either as static values or as dynamic ranges. Based on the risk assessment, risk reduction strategies can be implemented for hazards where the risk of harm is seen to be unacceptably high.

Because the traditional approach of risk reduction by separation of the human from the robot cannot be used for collaborative settings, the focus of the guidelines in TS 15066 is on influencing the design of the robot, the joint workplace and the collaborative task itself, to include protective measures that ensure the safety of human operators at all times. This may include re-design of tools and work pieces, e.g. to achieve smooth, but not sharp, surfaces and low weights, both of which influence the impact force in hazardous situations caused by direct contact with humans. To continuously track the position of humans within the collaborative workplace, a speed and separation monitoring system is essential. Where hazards arise out of direct contact with human operators, whether intended or unintended, a fast contact detection system must be in place to feed into a safety-related control system. This system must be capable of processing context-related information in real time and to activate protective measures when this becomes necessary. These are examples of runtime monitors and an important part of safety assurance at runtime, as we will see in the next section.

The impact force of dynamic contact and its duration, as well as the location (body region) of such contact—all key parameters for safety assessment—can vary greatly between collaborative tasks and, in particular, from human to human, even when restricting human-robot collaboration to shared workplaces within a flexible manufacturing environment.

This severely restricts the generality of calculations, as, in principle, human-specific information is required. It is still to be determined how this problem of person-specific characterization can be addressed. Potentially, a “calibration” phase may be required before operation starts, so that the robot co-worker can be customized to fit its human operator.

The ISO TS 15066 is expected to be publicly released later this year. It promotes a task-specific approach to safety assurance that requires the hardware and software, the work environment and task specification to be available for hazard analysis and risk assessment in their fully finished forms prior to the deployment of the collaborative robotic system. Furthermore, it is based on the assumption that it is possible to predict as well as counter all hazardous operation conditions prior to system deployment. This appears to be inherently at odds with the concept of teaching robots new tasks “on the fly”, which leaves the task identification, definition and training to the human operator, whose safety is of paramount importance. Hence, each newly learnt task, and also the learning process itself, must be safety assured. Thus, for any learning from demonstration technique to become viable in practice, safety must be an integral part of the learning process, directly embedded into the learning algorithms. Task-specific safety assurance, consequently, may need to be shifted to runtime, at least in part.

B. Assurance at runtime

A case for “Just-in-Time Certification” of adaptive systems has been made in [3]. Traditional assurance methods are based on the assumption that, prior to deployment of a system, the system is available in its final form for safety assessment, and that all operating conditions that the system will face while interacting with its environment can be predicted and analyzed upfront. Adaptive systems, however, are designed to modify their behaviour at runtime in response to changes in their environment or in the system itself. Such systems simply do not meet the assumptions on which traditional certification methods are based, because the time at which the behaviour of the system is finalized is shifted from system design to system deployment. This impacts on the time at which certification can be performed; it leaves at least part of the certification process to be completed at runtime. Adaptive systems, therefore, call for the development of novel approaches to certification, not to replace traditional approaches, but to complement these with techniques that can be used at runtime.

Robots that learn from demonstration are adaptive systems. They learn new tasks at runtime. The fact that a human is involved in the training as well as in the collaborative execution of the task is associated with benefits and challenges with respect to safety aspects. On one side, the human operator can influence learning so that the learning result complies with safety requirements. On the other side, however, the human operator is exposed to potential hazards during the learning process; this creates the obligation to protect her/him from these. Can “just-in-time” techniques support safety assurance in our context?

The provocatively named “just-in-time” certification approach proposed in [3] is firmly based on the use of formal methods, at design time and at runtime. It takes advantage of the observation that, if the behaviour of a system was fixed at design time, then safety assessment would focus on the pre-defined behaviour and determine whether its characteristics meet a set of pre-defined safety requirements. If the checking step could be automated, then its execution could reasonably be shifted to runtime. This, of course, necessitates encoding the safety requirements in a suitable form for runtime monitoring, e.g. as a model or a protocol to be adhered to. A monitor can then be formally derived from the model or protocol. At runtime, this monitor continuously checks compliance with the safety requirements, and prevents any behaviour that causes violations. An advantage of performing these checks at runtime is that out of the huge number of possible system behaviours, only the one that is currently being adopted needs to be checked. While, traditionally, such monitors are generated at design time and applied at runtime, the use of Runtime Verification techniques¹ enables the generation of such monitors at runtime, based on explicit models that capture the generic behaviour of system components and the safety requirements that must be satisfied.

In a similar way, “learning from demonstration” approaches could be constrained at runtime, based on suitable models or protocols, to deliver only learning results that are considered safe. Alternatively, or in addition, task-specific safety monitors could be generated. These prevent interactions which violate safety requirements at runtime. It is worth noting that safety-related control systems are already mentioned in the forthcoming standards for runtime monitoring and potential intervention as briefly indicated in Section II-A. In the next section we review “learning from demonstration” techniques and investigate opportunities and challenges to integrate safety assurance into the learning algorithms by design, as well as options to shift part of safety assurance to runtime.

III. OPPORTUNITIES FOR INTEGRATING SAFETY INTO THE LEARNING FROM DEMONSTRATION PROCESS

A. Learning from Demonstration (LfD)

To perform a task, a sequence of actions is applied to a given state of the world. Each individual action transforms the world state; the final action should result in a state that reflects the execution of the task. Finding an effective sequence of actions, i.e. a policy, to achieve a target state is a key challenge in robotics and automation. In “Learning from Demonstration” (LfD) robots learn a new task by watching the task being performed by a human or a robot teacher. The observations gained from watching the task guide a supervised learning process towards the development of a policy that the robot learner can use to perform the task. LfD offers an intuitive way for humans to communicate with robots. It enables non-experts to teach robots new

¹<http://runtime-verification.org/>

skills by simply demonstrating these to the robot. In flexible manufacturing, robotic assistants are used to support humans during the execution of a large variety of different tasks, each of which would normally require some level of re-programming or re-setting the robot. With LfD techniques this is not necessary, as new tasks are acquired by learning from example demonstrations. As such, LfD techniques facilitate human-robot interaction and support more flexible human-robot collaboration.

A variety of different machine learning techniques have been used for LfD; a recent survey is contained in [1]. In general, three core approaches for policy derivation can be distinguished according to [1]:

- a) those that learn directly how to map the robot's state observations to actions,
- b) those that derive a policy based on learning a world model and a reward function, and
- c) those that learn a policy by planning based on sequences of actions and their pre- and post-conditions.

Irrespective of the learning approach, the challenge is to ensure that safety is maintained during the learning process, and that the learning result satisfies safety requirements "by design". This necessitates embedding safety considerations directly into the learning algorithms. How this can be achieved is a research question that needs to be addressed before LfD can safely be deployed in practice.

The collaboration with robotic assistants is likely to change the nature of the work, the tasks involved, and the work environment [4]. For LfD it has been found that simple imitation or mimicking of the demonstration is often not sufficient for the robot to perform the task [5]. Instead, the objective of the task that is being demonstrated must be captured, so that a policy can be learnt that enables the robot to achieve this objective. The actual behaviour of the robot to realize its goal may differ from that demonstrated, especially when the trainer is a human rather than another robot. In [5] it was found that the robot's hand motion in a simple pendulum swing up task was quite different from the motion recorded for the human demonstrator due to differences in gripping technique and hand structure, which result in different task dynamics. In general, the bigger the physical differences between trainers and learners, the more likely it is that the learnt behaviour differs, although it achieves the same objective. This is an important finding and likely to be problematic in the context of safety assurance, which is task specific, as described in Section II-A. Even if the actions performed in a task demonstration satisfy safety requirements, the safety assessment may need to be repeated for the learning result, because the dynamics of the learnt task may differ enough from that of the demonstration for the original safety assessment to no longer hold.

The LfD approach in [5] provides a good example to illustrate how safety may be integrated into a model-based planning algorithm in the form of constraints that capture pre-determined safety requirements. The existing planner aims to find a policy that the robot can use to accomplish the target task. Amongst all the possible policies, the ones that

satisfy the relevant safety constraints are desirable. While including safety constraints into planning clearly increases the complexity of the learning task, this is necessary to ensure that the learning outcome complies with safety requirements. In [5] it has been shown that learning performance can be significantly increased when background knowledge is provided in the form of models that capture the physics of the task to be learnt. If the physical characteristics of a task are known upfront, could safety requirements be attached to these models to guide the learning towards safe policies? Could these enriched models then serve as the basis for the generation of runtime safety monitors?

B. LfD with Reinforcement Learning

Reinforcement Learning [6] is a widely used LfD technique [1] and a good example to illustrate the potential problems arising when robots learn new tasks "on the fly". The interesting feature of Reinforcement Learning is that policy development is guided by feedback given to the robot during explorative learning. Feedback is provided in the form of a function that rewards desirable and penalizes undesirable actions. Learners aim to maximise their cumulative reward. Based on the feedback, the robot learns which actions or sequences of actions are preferable to achieve a target goal. Thus, in Reinforcement Learning, policy development necessitates performing desirable as well as undesirable actions. This can result in robots violating safety requirements while learning new tasks. In an environment that requires close collaboration with humans also during the learning stage, this cannot be tolerated. Clearly, human operators need to be protected not only during the joint task execution in collaboration with a robot, but also during task transfer, i.e. during the LfD process.

An adaptation of Reinforcement Learning that includes future directed rewards in the form of interactive guidance given by humans during the learning process has been presented in [7]. The resulting learning system can dynamically switch between explorative and guidance-based learning. This has been achieved by modifying the learning algorithm so that it accepts guidance when it is available; if not, then the algorithm works by randomly selecting actions and observing the associated reward. Guidance is given by a human teacher who constrains the robot's action selection, e.g. by focusing on a particular object, the explorative learning is being restricted to the smaller and more relevant set of actions related to that object. The result is a more rational choice of actions compared to the random action selection that would be made by algorithms without guidance. The benefits include, amongst others, improved learning performance and a decreased number of failed trails. This leads to more understandable behaviour of the learner and a more fulfilling experience for the human teacher. It seems plausible that a similar approach could be used to achieve both, safety of the learning process and of the learning result, by biasing action selection to those actions that satisfy safety requirements. To achieve this, a method

needs to be found to formalize safety requirements as high-level policies that can guide learning.

C. *Virtual and mixed reality environments for LfD*

It has been proposed to transfer LfD into virtual environments to reduce the time, labour and cost of real-world development methods [8]. Virtual environments would also make the LfD considerably safer for human operators. In [8] modelling first creates a virtual agent, termed the “virtual human”, who takes the role of the human in LfD within a virtual environment. The virtual human is controlled by a human operator to learn a human behavioural model which serves as a basis for executing actions during the demonstration part of the learning. Another virtual agent, termed the “virtual learner”, observes the virtual human’s actions in order to learn behaviours that enable it to collaborate with the human. This phase of the learning process is called “behavioural learning”. In the second learning phase, the “collaborative learning”, the virtual learner then learns how to collaborate with the virtual human. Finally, once learning has been accomplished in the virtual environment, the results can be transferred to a real robot or a software agent.

Safety compliance could reasonably be evaluated, at least in a first instance, in such a virtual setting. Only those learning results that have passed safety assessment in the virtual environment would then be applied to the real robot. Of course, this necessitates a sufficiently accurate model not only of the human and the robot learner, but also of the environment in which the interaction will take place, i.e. the collaborative workplace. The major shortfall of the approach described in [8] is that it does not generalize to complex real world scenarios, where interaction is required with different humans. As it stands, multiple humans would need to be modelled and behaviour as well as collaborative learning would need to be repeated for each human model. The challenges of accommodating variability, both between multiple demonstrations of a task by the same operator, and between demonstrations of the same task by different operators, need to be addressed to develop a more generic approach to LfD, not only in virtual environments.

In [9] mixed-reality testbeds are used to support incremental development of systems that involve humans, robots and software agents with the goal to reduce costs and risks compared to testing in a real-world environment. The operation of these systems depends on a variety of factors, including, but not limited to, those of the robot hardware, e.g. the characteristics of the sensors and actuators, the features of the environment, e.g. the collaborative workplace including tools and materials, and, most importantly, the behaviour of the human operators, resulting in a complex test environment overall. To facilitate early and fast validation, the components in the physical test environment can be replaced by virtual models in incremental steps, either fully or partially. The resulting mixed-reality, multi-level testbed integrates models of different fidelity and size, so that validation can be performed at the level of abstraction that delivers the accuracy appropriate for the respective test objective.

The degree of virtualization ranges from full virtualization of all system components, as described in [8], to mixed-reality settings where different system components are virtualized to different degrees. The latter include hardware-in-the-loop simulation environments to increase the fidelity of the hardware components in the testbed, as well as human-in-the-loop virtual environments where human operators work in a virtual reality setting so that the aspects of human behaviour that are difficult (if not impossible) to capture with virtual models become an integral part of the testbed.

In the context of human-robot collaborative manufacturing, the fluctuations of human performance due to factors such as fatigue, stress, lack of attention or concentration could thus be determined, and their effects assessed, without exposing the human operator to the risks inherent in testing these in the physical environment. Could learning from demonstration be entirely shifted to virtual or mixed reality environments to protect human operators during learning?

Many LfD techniques assume that for each action a well defined, deterministic state transformation can be specified, and that all system states are known and thus can be defined upfront [1]. This almost certainly does not hold for real world settings, especially those involving humans. In the next section we take a human-centric view on these aspects.

IV. HUMAN FACTORS

Humans have evolved as social animals over thousands of years. They are highly sensitive to signals sent by other humans such as in collaborative tasks [10]. Any movement observed from another agent (evolutionarily another human or an animal) will not only be interpreted to have a purpose, but to be context-dependent and meaningful [11]. For example, the speed with which a person hands over an object to another person will vary depending on the physical abilities of the two people involved in the interaction (e.g. an adult handing over a cup to a small child or to another adult), the type of object (e.g. a glass of water or a hot bowl of soup), and their intent (e.g. slow movements might be a warning to the other person to be careful when taking the object, but could also indicate reluctance to let go of it). Therefore, humans will usually rely on the context they are in and accompany their interactions with a range of (mostly nonverbal) signals (such as eye gaze or facial expressions, body posture) with the consequence of disambiguating their intentions. Humans tend to anthropomorphise moving agents that are (seemingly) able to adapt their behaviour in a dynamic way and attribute to them social cognitive abilities of their own [12]. This creates an intuitive expectation in the human about the behaviour of such agents, which can be modulated only by experience.

Imagine a very simple scenario in which a robot repeatedly performs a single task which is highly predictable in its order of events, but requires the robot to move within an arm’s reach of the human (e.g. the robot picks up an object from a conveyor belt and holds it for the human to work on). To make both the robot’s and the human’s tasks efficient and to avoid collision between the human’s arm or hand and the

robot itself, both human and robotic movements need to be exactly orchestrated [13]. This entails the implementation of a cognitive model of human action in the robot that monitors and predicts human action at a very short time scale, including human inter- and intra-individual movement variability as well as cognitive performance inconsistencies that are dependent on individual factors such as fluid intelligence [14], [15]. Measures of intra-individual movement variability on a longer time scale such as variability induced by fatigue are already widely used in Human Factors (e.g. heart rate [16], [17], alpha frequencies in electroencephalography to detect drowsiness [18], [19]).

Less common psychophysiological methods would be required to provide the robot with dynamic information on a far shorter time scale, such as tracking eye gaze to continuously monitor the human's focus of attention [20] and predict mind wandering [21], or 3D motion capture information to track the human's arm movements [22]. Models on Joint Action Understanding in humans [10] might give a first idea about the cognitive architecture necessary within the robot.

Safety solutions to certification of specific robotic tasks for HRI as given in the above scenario might seem complex and require a range of control mechanisms, all regulating and controlling the human's behaviour. However, they can, to large extents, rely on the inclusion of already existing technology and methodology in Human Factors.

Imagine next a situation in which the robot selects between different tasks depending on the context and is therefore not 100% predictable at all times. This forces the human to deal with uncertainty about the robot's next actions. In such a scenario, it becomes even more important for the robot to send effortlessly understandable signals that disambiguate its actions for the human. This enables the human to maintain a sufficient level of awareness of the state and actions of the robot. In fact, transparency together with control have been found to be more important to human operators than increased autonomy [23]. This is because, as the complexity of the jointly performed task grows, so does the importance of addressing mutual dependence to sustain team performance and the necessary level of safety. Increased autonomy without addressing interdependence has been shown to result in sub-optimal performance [23].

V. SUMMARY AND CONCLUSION

Assurance methods have evolved over time, from isolation of humans from robots, to a task-based approach in the forthcoming technical specification, TS 15066. There is, however, still a long way to go to establish assurance methods for systems that acquire new behaviour at runtime, such as robotic co-workers that learn from demonstration.

We propose that the question of safety needs to be addressed as an integral part of the very process of teaching the robotic co-worker, and have highlighted opportunities to extend existing LfD techniques accordingly. Furthermore, to achieve high levels of safety and ultimately trust, the robotic co-worker must meet the innate expectations of the humans it works with. This necessitates equipping robotic co-workers

with a cognitive model of human action and the ability to clearly communicate their intentions to human operators in a timely manner.

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