

Human-Centric Digital Twins: Advancing Safety and Ergonomics in Human-Robot Collaboration

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Abstract. Human-Robot Collaboration combines the reliability of robots with human adaptability. It is a prime candidate to respond to the trend of Mass Customization which requires frequent reconfiguration with variable lot sizes. But the close contact between humans and robots creates new safety risks and ergonomic factors like robot-induced stress need to be considered. Therefore we propose a human-centric Digital Twin framework, where information about the human is stored and processed in a dedicated Digital Twin and can be transmitted to the robot's Digital Twin for human-aware adaptations. We envision and briefly discuss three possible applications. Our framework has the potential to advance collaborative robotics but inherits technical challenges that come with Digital Twin based approaches and human modelling.

Keywords: Human-Robot Collaboration · Human Digital Twin · Cognitive Digital Twin · Human-Centric System · Robot Safety · Ergonomics.

1 Introduction

Human-centric systems are designed following the human centered design paradigm which focuses on people's needs first [10]. Important pillars of the design philosophy are, among others, usability, accessibility, ethical considerations and user empowerment. The paradigm has been applied successfully to develop, for example, healthcare information systems, interfaces for user electronics or Smart Homes, especially for elderly care. Human-centric systems are not only implemented to support consumers or patients, but also workers in an industrial context. In manufacturing, the collaboration between humans and robots can benefit from human-centric design approaches.

Where appropriate, industry has adopted automation to enable efficient and cost-effective production of large lot sizes, keeping unit cost down. But the high upfront cost of fully automated systems are prohibitive for small production runs. Additionally it is costly to change the configuration of a fully automated production line, leading to limited flexibility when it comes to customizing a product for a customer segment or an individual's specific demands. As a polar

opposite manual labor is highly flexible and, provided the right training and instructions, can customize products quickly to respond to demand, but at a high unit cost. Therefore a compromise between cost-effectiveness and flexibility is desirable for products that should be highly customizable with variable lot sizes [38]. A prime candidate to achieve this is Human-Robot-Collaboration (HRC) (see Figure 1) which combines the repeatability, accuracy and strength of robots with the flexibility and versatility of humans.

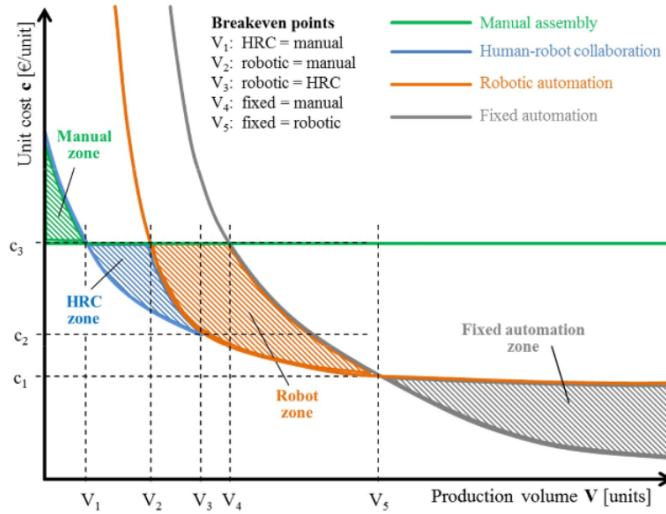


Fig. 1. Economic viability of HRC as presented in [42]. The blue zone represents the production volumes for which HRC provides the best unit cost and thus is economically viable.

Interactions between humans and robots have evolved over time, starting with mere coexistence in the same physical space with completely independent operations. Eventually the interactions between humans and machines deepened, Wang et al. [61] distinguished between Coexistence, Interaction, Cooperation and Collaboration between Humans and Robots. For the remainder of this paper we exclusively focus on Human-Robot-Collaboration, which means that both actors are sharing the same workspace, resources and tasks while direct physical contact is allowed.

With the close contact between robots and humans comes a non-negligible risk of injury which motivates extensive research into robot safety methods and collision avoidance in particular. Real-time situational awareness is a common challenge and required to estimate distances or distinguish voluntary from accidental contact. Robots need to be more flexible and adaptable in their programming to work with the uncertainty that human behaviour introduces into the system. Nonetheless successful HRC implementations can improve ergonomics

[36] by minimizing mental and physical fatigue by assigning repetitive and heavy lifting tasks to the robot. But poorly implemented systems can induce stress in the human worker and erode trust in the machine thus there is a need to track the human state and ergonomic metrics for good collaboration.

In the field of system control, safety has always been a major concern for industrial setups. Recognizing this, the Digital Twin (DT) has been identified as a practical and efficient solution. Given its potential, we are inclined to propose a framework that integrates DT. By emphasizing human interaction and involvement in the process, the DT is positioned not only to bolster safety measures but also to refine and optimize ergonomics. Through behavioural models additional information about human intent can be exploited to ensure safety through adaptation of the robot’s movement. While tracking the human state allows the computation of ergonomic indices for improved well-being or adapt operation speed for comfort. A DT is a continuously updated digital representation of the twinned entity. It centralizes data of the given entity, can run models to simulate situations before they occur, or emulate the system to possibly mitigate or prevent dangerous situations and failures. DT and twinned entity are connected via a bi-directional data link; captured data from the entity is fed into the DT to update models; and the DT returns feedback, which can range from suggestions to commands, to change the state of the twinned entity. Our framework is composed of two separate DTs; **(i)** A dedicated Human Digital Twin (HDT) [46] which gathers data from the human worker and models its intent, behaviour and well being; **(ii)** A Cognitive Digital Twin (CDT) [47] that utilizes cognitive functions to interpret the robot’s interactions, enhancing its ability to align its operations with the human’s anticipated actions and intents.

The remainder of the paper is structured as follows; Section 2 presents the state of the art for assembly tasks in HRC work cells with a special focus on the limitations and challenges in safety and ergonomics; in Section 3 we present a DT based approach to address perceived gaps in the state of the art; Finally in Section 4 we conclude and provide research directions.

2 State of the Art

Multiple core challenges of HRC are succinctly expressed by Wang et al. [61]: *“An essential aspect of HRC is how to cope with human ergonomics, process time, emotions and reaction during collaboration, and safety aspects.”*

While a wide array of challenges exist in HRC we choose to focus on, and explore, two dimensions: **safety & ergonomics**. Both lead back to problems with real-time situational awareness and integrating information about the human state and behaviour. Therefore human-centered approaches are particularly applicable to address these challenges. It was in this context that the notion of DT was introduced. DTs offer a precise digital replica of a real system or process, enabling detailed simulations and analysis. These tools are proving essential in tackling and solving the challenges of HRC. In what follows, we explore in depth the applications and implications of DTs in this context.

2.1 Safety

The merits of HRC are discussed in [30] where Kruger et al. make the case for how robot reliability and human adaptability can enable a new generation of assembly processes. Safety becomes a prime concern as soon as the physical separation between human workers and industrial robots is no longer guaranteed. HRC, by definition, allows physical contact between human workers and robots making physical separation inherently impossible.

In the industrial sector, many robots operate as Cyber-Physical Systems (CPS), optimized for performance and the completion of specific tasks. Faced with the rapid evolution of HRC, Yilma et al. [64] introduced an innovative approach to Industry 4.0, based on the Cyber-Physical-Social Systems (CPSS) paradigm. While human aspects and subtleties are frequently omitted from traditional CPS-centric models, the CPSS methodology aims to resolve this omission. It aims to strengthen collaboration while guaranteeing security. Thanks to artificial intelligence, CPSS can assimilate and interpret human behaviors, making robots, especially those based on CPS, more effective collaborative allies.

In [61,60] the causes for HRC accidents are organized in three categories; Engineering failures, human errors, and poor environmental conditions. For robotics and machinery in general, engineering failures are addressed in the design phase and guidance is provided in ISO 13855 [25]. The unavoidable physical contact between robots and humans in HRC setups required an adaptation of standards, which lead to ISO/PDTS 15066 [26]. It provides valuable guidance on risk assessment, safety features, workspace design as well as task and process design. Overall safety in robotics is a well researched subject, nonetheless the challenging context of HRC requires further investigation on how to enable setups that can operate at relatively high efficiency and speed without compromising safety.

Research in HRC safety can be categorized into three categories; **(i)** understanding injury mechanisms and related standards; **(ii)** limiting the severity of an impact; **(iii)** active collision avoidance. In the first category, Haddadin et al. [19,20,21] made major contributions with their work on injury mechanisms of collisions that might occur during HRC task execution. Further research from Haddadin et al. [18] establishes that safety is guaranteed for robot velocities below 2.7m/s and in [22] the link between mass, velocity, impact geometry and resulting injury is described in detail. Instead of limiting operational velocity, Laffranchi et al. [33] proposed to regulate the energy of the system instead. Earlier research in [63] analyses pain tolerance of humans and establishes an early method to reduce robot velocity upon impact, which allows the human operator to reflexively withdraw and avoid serious injuries and pain. More recent research introduces additional constraints to the control algorithms based on newly introduced safety indicators [43]. Depending on the distance between robot and human operator the kinetic and potential energy in the system is reduced to limit the energy that could be dissipated in the event of a collision.

Detecting collisions and reacting appropriately represents a second major category of research in HRC safety. Unmitigated movement of a robot after an unwanted collision can lead to severe pain and injury. As contact between robot

and human is expected in HRC it is not appropriate to stop operations as soon as any physical contact occurs, instead more subtle methods are required. On the hardware level the addition of joint torque sensors enabled a new set of safety features. Tonietti et al. [58] adjusts the stiffness of actuation to inherently guarantee safety. Park et al. [52] developed a passive safety mechanism through non-linear stiffness. During normal operations high stiffness is maintained, but upon impact, that exceeds a set threshold force, the stiffness drops quickly. In contrast Geravand et al. [17] base their control architecture on the motor currents and joint velocity without the need of additional torque sensors. Kokkalis et al. [27] compare provided motor currents with the expected current needed for the planned trajectory to limit forces during contact. In a similar approach [45] uses reference torque and actual torque to the same end, while [37] use Neural Networks to detect torque disturbances. A last set of approaches uses additional external sensors, such as optical cameras [13,31,16] or depth sensors [8,14] to detect collisions.

Avoiding collisions altogether is approached from different angles by researchers. A large swath of research uses on or the combination of detection systems such as, time of flight cameras (or other depth sensors) [15,3,1] or optical [57] cameras. Creating 3D models of the robot, environment and/or human worker is sometimes used in addition to the chosen sensing systems [44,62] to enable better distance estimations. Some approaches put the human worker at the center of their investigation by tracking their movement, either with wearables or external cameras to ultimately include human behaviour [66] as a parameter for robot adaptation [34]. Augustsson et al. establish safety zones [5] based on which the robot can adapt when a human enters the zone. In this case the data about the human is communicated to the robot for adaptations. Efficient real-time communication is generally a challenge and includes communicating the human position to the robot as well as changes in assembly order or settings to the human [6].

Decades of Robotics safety research have lead to hardware adaptations, and methods that substantially reduce the risk of severe injuries. Force and speed limits, alongside collision detection and appropriate reactions upon impact mitigate both pain and injury severity. But, we believe that further research is desirable in the field of collision avoidance. Increased situational awareness, including the internal state of the human operator (e.g. stress, behavioural patterns), could enable less restrictive and more dynamic speed adaptations and enable increased efficiency of HRC work cells. In Section 3 we introduce a DT based approach to address the perceived limitations of traditional setups.

2.2 Ergonomics

In HRC setups robots should support the human worker to fulfill the defined task as a human-robot team and adapt their own behaviour to make the human comfortable, improve ergonomics performance and keep task completion time low [61]. Ergonomics encompasses not only physical stress, which can be induced by e.g. lifting heavy loads, but also mental stress. Both mental underload, from

monotonous tasks, and overload, typically from overstraining or high pace, need to be addressed in HRC research.

A necessary component of HRC is that the human team member accepts to work with the robot. Poorly adapted robot movement can induce stress, erode trust and ultimately lead to the loss of propensity to work with the robot. Trust is a major parameter for successful HRC setups and has been studied extensively by Hancock et al. [23]. The dominant factor that can erode trust is the performance of the human-robot team, while environmental and human factors have a more limited impact. The distance between human and robot alongside the robot’s movement speed has a direct impact on induced stress [4]. The more general impact of robot movement on the human affective state has been investigated in [32]. Adapting the robot’s movement by designing human-aware systems is a promising approach that has found success in the field.

Research addressed the problems through better motion planning based on human-aware systems. The movement needs to be predictable, and perceived as safe. Multiple papers seek to improve motion planning and task allocation by including information about the human worker; such as the human’s goals [53], mental model [49], perception of robot movement [51,11], next subtask [24] or intended motion [59].

Many promising approaches to improve fluency of HRC systems and ergonomics rely on understanding the human worker’s behaviour and state better. In Section 3 we propose the use of HDT to gather human worker data and relevant models for better adaptive systems.

2.3 Digital Twins

Safety, a long-underestimated major concern in robotics research, has become a central preoccupation as intelligent collaborative robots, commonly known as cobots, are increasingly integrated into various industries. These cobots are equipped with sensors that enable them to detect and react to their environment, guaranteeing safe physical interactions with humans. These sensors not only detect the presence of humans and potential obstacles, but also gather complex data on cobot movements and forces, such as joint position and compliance monitoring. Faced with this safety challenge, it is imperative to develop advanced simulation models known as digital twins (DT). These are defined as, “*A set of adaptive models that emulate the behaviour of a physical system in a virtual system getting real time data to update itself along its life cycle. The digital twin replicates the physical system to predict failures and opportunities for changing, to prescribe real time actions for optimizing and/or mitigating unexpected events observing and evaluating the operating profile system*” [55]. These DT enable scenarios to be recreated [54] and tested virtually [29]. This data-driven approach ensures that cobots can interact safely with humans, marking a significant advance in automation within the manufacturing sector. Safety in HRC setups is further delved into with a study [9], where a mixed-reality approach is proposed to enhance safety. This method employs sensors to measure the real-time safety distance between humans and cobots. Further enhancing the

capabilities of DT, Droder [12] introduces a machine learning method for industrial cobots to avoid obstacles and people, using the nearest neighbor approach for trajectory planning and neural networks for detection.

With the aim of allowing DTs in virtual reality to guide the safe implementation of human-robot collaboration strategies in future factories, Oyekan [50] established a DT workshop to study human responses to both predictable and unpredictable cobot motions. The findings indicated that real-world human reactions to robotic behaviors were consistent with those observed in the DT virtual environment. It is essential to create an accurate and consistent DT model that captures the physical components and their interactions. With this in mind, a quadruple DT model has been suggested [39], encompassing separate models for the cobot, the individual, the collaborative framework, and their interrelationships.

In the field of ergonomics, the introduction of Digital Human (DH) technology to the DT-controlled HRC represents a significant step forward, emphasizing human centrality in a production context. This system [41] captures and simulates operator movements and physical constraints in real time, providing a precise ergonomic assessment platform. It is structured around three integrated modules: the first is a virtualized robotics module offering direct, real-time control of the PLC; the second is a DH module specifically dedicated to the analysis and simulation of operator actions; and finally, a production management module which guarantees adapted planning taking ergonomic criteria into account.

The DT has been employed in the design and reconfiguration of assembly systems. Kousi et al. [28] has modeled production parameters at different levels and updates them dynamically using data from 2D-3D sensors, combining geometry and semantics to obtain an overview of the production process.

DT functions, like monitoring, prediction and optimization, offer effective strategies for HRC assembly. Malik's [40] study introduces a DT framework aimed at optimizing the design, construction, and control of human-machine assembly collaborations. Through computer simulations, a constantly updated digital model of the collaborative environment is maintained, ensuring timely improvements and mirroring the physical setup. Similarly, Bilberg's [7] research focuses on an object-oriented simulation of a flexible assembly cell, integrated with a cobot to work alongside humans. Beyond traditional virtual models, this DT emphasizes real-time control, dynamic task allocation between the cobot and human, and adaptive cobot programming based on the task sequencing.

DT, while useful in a variety of fields, have certain limitations when applied to HRC. One major limitation is their limited ability to anticipate and adapt to unpredictable human behavior in dynamic work environments. In addition, DT may struggle to model safety accurately enough to ensure safe interactions between cobots and human workers. This highlights the need for a better understanding of the human processes at the core of these interactions. The notion of cognition focuses primarily on knowledge and understanding [47]. It encompasses the processes by which sensory inputs are transformed, stored, and used

[48], including aspects such as attention, reasoning, learning, memory, perception, problem solving, and knowledge representation, among others [2].

In an HRC context, where safety and ergonomics are major concerns, it becomes clear that advanced cognitive capabilities are required. This is where the Cognitive Digital Twin (CDT) comes in, which is “*a digital representation of a physical system that is augmented with certain cognitive capabilities and support to execute autonomous activities; comprises a set of semantically interlinked digital models related to different lifecycle phases of the physical system including its subsystems and components; and evolves continuously with the physical system across the entire lifecycle*” [67]. The CDT possesses knowledge manipulation and problem-solving abilities. These cognitive capabilities include detection, reasoning, and self-learning, enabling continuous and proactive adaptation.

Research such as that conducted by Shi et al. [56] on a CDT framework for manufacturing systems with HRC based on 5G communication networks illustrates the increasing importance of CDT in the manufacturing field. The concept of CDT in [65], thus provides the ability to dynamically handle more complex and unpredictable situations through enhanced computational capabilities. As an emerging concept, CDT has not yet been widely implemented and verified in the industry. Most published studies explore the theoretical perspectives of CDT or focus on its vision. Nonetheless, there are ongoing studies and projects targeting its practical feasibility in diverse industry scenarios. Notably, the active EU project COGNITWIN [67] aims to enhance the cognitive capabilities of existing process control systems to enable self-organization and address unpredicted behaviors.

3 Proposed Research

In this section we propose a DT based approach to respond to challenges in HRC safety and ergonomics. We propose an adapted architecture for DTs of agents, discuss their application in the context of HRC. Two functionalities of DTs are of interest, namely emulation and simulation.

3.1 Single Agent Digital Twin

For each physical entity, or more precisely agent, we propose to instantiate a dedicated DT that gathers all the data coming from the twinned entity, and holds all the models describing and acting upon the twinned entity. Additionally the ability to receive data from the environment or other physical entities is required to provide the relevant context for some of the models. Figure 2 depicts the essential elements and their interactions required to build a DT of an agent. *Data* from the *Twinned Agent* is fed to the *Agent Digital Twin* and stored in the *Data Storage* alongside data from the *Environment* that is needed to give required context. *Data* is used by the *Models* to track and predict parameters of the *Twinned Agent*. The result of running a model can be fed back into the *Data Storage* to update relevant parameters or trigger a feedback to the *Twinned*

Agent. For cobots the feedback could be a change in operational mode while a human agent can not be directly controlled but only influenced via suggestions. The last element is the *Agent Digital Twin*'s interaction with other agents in the system. Through an *Access Interface* data can be shared between agents and fed to the relevant models to adapt behaviour accordingly. The *Co-Simulation Interface* provides the ability to run simulations of what-if scenarios involving multiple agents. In this case simulated data needs to be provided as both the physical *Environment* and *Twinned Agent* are decoupled for simulation runs.

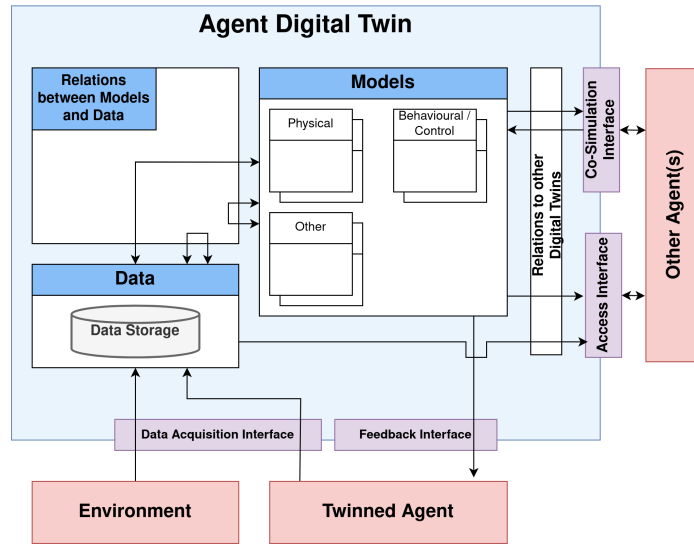


Fig. 2. Digital Twin Architecture for an Agent. Adapted from the Human Digital Twin reference architecture proposed by Löcklin et al. [35].

3.2 Digital Twins for Human-Cobot Collaboration Systems

Considering the specific case of an HRC scenario, there will be two DTs; a *Human Digital Twin* and a *Cognitive Digital Twin*, see Figure 3 for the proposed architecture. The physical layer is composed of a *Human* alongside a *Cobot*. Both agents have physical interactions with each other and the *Environment* itself. Data is gathered from both agents to feed into their respective DTs, which follow the previously described architecture from 2. A *Communication Module* supports the exchange of data between the two DTs which can run models to track the state of the system and send feedback to their twinned entity. Feedback to the *Physical Layer* is managed by a *Control System*, which can reallocate and reschedule tasks dynamically, or change the operational mode of the *Cobot*.

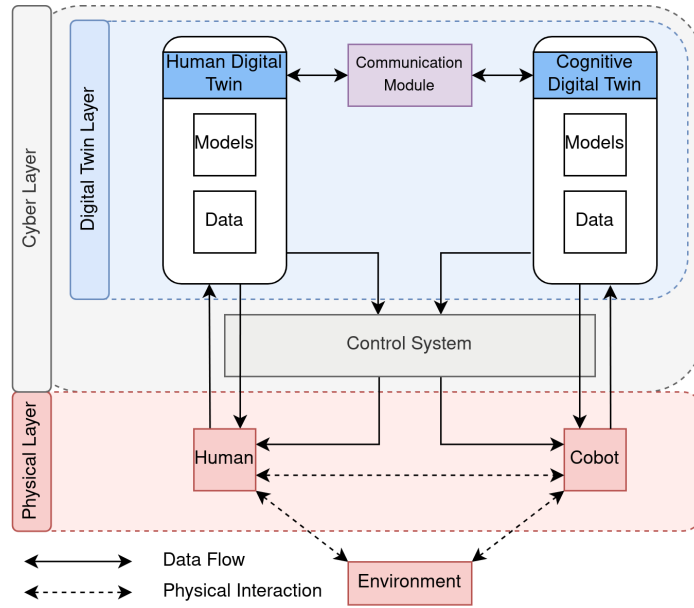


Fig. 3. Digital Twin based approach for HRC systems with one human worker and one Cobot. Dashed lines represent physical interactions while full lines represent data flows.

The *Human Digital Twin* gathers data from the human worker, which can include static data (e.g. age, skills, personality) and live data (e.g. biometrics, video, sound). Through models meaningful information, such as ergonomic indices, can be computed, stored and shared with the *Cognitive Digital Twin* and *Control System*. Receiving live information about the state of the human worker is the backbone of human-aware cobot adaptation.

The *Cognitive Digital Twin*, on the other hand, utilizes data received from the *Human Digital Twin*, along with its own data and knowledge models, to perform more advanced analyses. The *Cognitive Digital Twin* harnesses its cognitive functions to perform various tasks. Through perception, it interprets sensory data like facial expressions and voice tone. It employs reasoning to detect patterns and anomalies, drawing from its memory of past experiences. This informs its decision-making, allowing it to suggest adjustments like altering the cobot's parameters or task assignments based on real-time observations.

We see two possible adaptation that are possible in the DT based HRC system; (i) reallocating or rescheduling tasks through the *Control System*, (ii) changing the operational mode or settings of the *Cobot*. Example changes for the *Cobot* include arm velocity and trajectory selection. For illustration purposes we describe three cases where our framework could be applied successfully.

Collision avoidance The *Cognitive Digital Twin* leverages real-time emulation capabilities to coordinate collision avoidance strategies. Data is gathered from wearable devices or static cameras to feed *the Human Digital Twin*, which calculates estimated positions of the human operator’s head and arms based on this data. Simultaneously, data concerning the cobot’s joint and end effector positions is continuously monitored and shared with the *Cognitive Digital Twin*. The *Communication Module* facilitates data exchange between human and cobot positions, which is then analyzed by a collision avoidance model stored within the *Cognitive Digital Twin*. The advantage is the possibility to connect models from the *Human Digital Twin*, for example a intention model, with the collision avoidance model of the *Cognitive Digital Twin*. The adaptive behaviour can incrementally be enhanced by considering increasingly complex aspects of human behaviour.

Ergonomic improvements In an analogous fashion information from the human worker can be fed to a dedicated model of the *Cognitive Digital Twin* to adapt the movement in order to decrease induced stress. To improve the human’s comfort not only the movement of the cobot can be adapted but also the allocation of tasks. The *Control System* is kept up to date about the task progress of both agents but can also receive information about the state of the human worker. A threshold based approach could be used to trigger dynamic reallocation of task when stress or fatigue increases too much.

Emulating cobot reactions under extreme human behaviour The DT framework can be used to run emulations by decoupling the physical entities from the system and feeding in emulated data. In the context of HRC this opens up the possibility to test the cobot’s adaptive response under extreme human behaviours without putting any human at risk of injury. The ability to emulate edge cases becomes especially important if the adaptive behaviour relies on Machine Learning, knowledge-based systems (symbolic AI) or hybrid approaches. Such integrated approaches can show unintended behaviour when encountering edge cases, making emulation vital.

4 Conclusion and Discussion

We discussed how a human-centric, DT based, approach can be applied to respond to challenges in Human-Robot Collaboration (HRC). We explored, in detail, the state of the art two particular problems; safety & ergonomics. Extensive safety research has established limits to velocity, speed and energy for human safety. Furthermore methods to limit the severity of an unwanted collision are well established. The most challenging approach to safety is avoiding unwanted collisions altogether, which requires excellent situational awareness. Ergonomics research established a link between robot movement and the human’s feeling of safety, trust and stress. The human experience and well-being can be improved

through adaptive motion planning and dynamic task allocation but requires a good understanding and tracking of the human state.

From the challenges in safety and ergonomics we identified situational awareness to be particularly important for successful HRC implementations. To achieve excellent situational awareness it is necessary to track the human state and account for the behaviour and intent of humans. As an additional benefit ergonomic adjustments could be made using the tracked data about the human worker.

In our discussions on HRC, we have highlighted the growing importance of safety, particularly with the emergence of collaborative robots. These cobots, equipped with advanced sensors, guarantee safe interactions with humans. Having explored the state of the art in the application of DT in HRC, it is clear that DTs play an essential role in simulating and predicting interactions to enhance safety. Digital Human (DH) technology reinforces this vision by faithfully reproducing human movements to provide a complete ergonomic assessment. However, despite the considerable advantages of DHs, they face the challenge of anticipating unpredictable human behavior. This is where the CDT comes in, adding advanced cognitive capabilities to traditional DT. Although CDTs represent a promising advance, their practical implementation remains largely theoretical.

We proposed a DT based framework where each agent has its own dedicated Agent Digital Twin (see Figure 2). Applied to a HRC system it translates to a human and cobot, each with their Digital Twin (see Figure 3). Through a communication module data can pass between the Digital Twins to run models that require awareness of each other’s state. The Human Digital Twin is explicitly designed to gather the data, and run models, required for human-aware approaches for safety and ergonomics. Likewise, the Cognitive Digital Twin is designed to analyze this data in greater depth, thus promoting anticipated adaptations during human-robot interactions. We briefly present three use cases for our framework; **(i)** Collision avoidance models can be supported with human intent models; **(ii)** Stress can be reduced by adapting the cobot’s movement or dynamically reassigning tasks, **(iii)** Cobot reactions under extreme human behaviour can be emulated without putting humans at risk.

Human-robot collaboration, particularly through the use of a DT, presents multiple challenges. The intrinsic complexity of human behavior poses modeling difficulties, often resulting in discrepancies between the DT’s predictions and real-world outcomes. Additionally, these models might lack the adaptability to cope with rapid behavioral changes, necessitating substantial data for training. The real-time demands of tools like Computer Vision can introduce performance bottlenecks, making the system’s speed a paramount concern. Task design for such collaborations is crucial; poorly planned interactions can lead to inefficiencies or even failures. Navigating the regulatory landscape while employing these technologies is another consideration. Moreover, when tapping into personal metrics, such as biometrics, there’s an added emphasis on securing that data, ensuring its safety and confidentiality.

With a view to future research directions in human-robot collaboration, the distinction between HDT and CDT models is crucial. For HDT, a thorough exploration of human models is necessary to ensure a faithful, nuanced digital representation of the individual. At the same time, for CDT, it's crucial to identify and integrate the cognitive functions representative of robots. Once these elements have been established and differentiated, they can be effectively applied to specific use cases, laying the foundations for more harmonious and productive human-robot collaboration.

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