An Aggregated Digital Twin Solution for Human-Robot Collaboration in Industry 4.0 Environments

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Abstract. The digital twin is a powerful concept and is seen as a key enabler for realizing the full potential of Cyber-Physical Production Systems within Industry 4.0. Industry 4.0 will strive to address various production challenges among which is mass customization, where flexibility in manufacturing processes will be critical. Human-robot collaboration – especially through the use of collaborative robots – will be key in achieving the required flexibility, while maintaining high production throughput and quality. This paper proposes an aggregated digital twin solution for a collaborative work cell which employs a collaborative robot and human workers. The architecture provides mechanisms to encapsulate and aggregate data and functionality in a manner that reflects reality, thereby enabling the intelligent, adaptive control of a collaborative robot.

Keywords: Digital twin · Collaborative robot · Human-robot collaboration · Industry 4.0 · Cyber-Physical Production System

1 Introduction

The fourth industrial revolution, characterized by the implementation of Cyber-Physical Production Systems (CPPS) involving vast networks of cognitive, interconnected and communicating devices, is bringing major changes in the manufacturing industry. The increase in demand for customized products, along with the new capabilities brought about by Industry 4.0 technologies, is causing a manufacturing paradigm shift from mass production to mass customization.

The importance of Human-Robot Collaboration (HRC) is increasing, as it provides, among other things, a means to attain the required manufacturing flexibility. HRC offers the advantage of combining a robot's speed, power, accuracy, repeatability and insusceptibility to fatigue, with the agility, intelligence and perception of humans.

It is often perceived that the result of the fourth industrial revolution will be full robot autonomy in 'dark factories'. However, due to the lack of technology and high complexity involved in automating intricate tasks, full robot autonomy, especially in changing and unstructured environments, will remain out of reach for the foreseeable future. Developing the building blocks of collaborative robot systems, which will enable

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robots and humans to work in collaboration - building on each other's strengths - is thus of great interest [1]. This calls for the development of technologies enabling learning, cooperating and coordinating machines [2, 3].

Conventional industrial robots lack the ability to collaborate with humans. On the other hand, new-age robots – better known as collaborative robots or *CoBots* – are designed to be intrinsically safe for operation alongside and in collaboration with human workers within collaborative workstations. CoBots address three main challenges: safety, rapid programmability, and flexible deployment and re-deployment.

CoBots achieve their collaborative capabilities by incorporating several safety features, such as force and power limits, momentum limits, position limits and orientation limits. On impact with a human or an object, most collaborative robots are designed to stop moving immediately, or to move away from the point of impact. Although collaborative robots are designed with these inherent safety features, this does not mean the collaborative application will be safe. For instance, a CoBot manipulating a sharp object is unsafe whether the speed and impact force can be limited or not [4].

The development of CoBots has brought solutions to some of the problems that plagued HRC implementation in the past. However, there are still numerous challenges that need to be overcome before collaborative robots can be efficiently and effectively implemented in HRC applications, to bring about real competitive advantage for manufacturing businesses. These challenges include: addressing the relatively slow speed of operation of collaborative robots; ensuring that collaborative workstations conform to safety standards; maintaining robot effectiveness in chaotic environments filled with uncertainty, and enabling real-time robot motion planning and control.

The objective of this research is to address some of these challenges through a digital twin (DT) solution, which aims at enabling intelligent control of the robot to achieve improvements in throughput, safety and efficiency. Presented in this paper is an architecture for the implementation of this DT solution.

The first section of the paper presents background into: HRC, challenges faced when trying to achieve high levels of collaboration, and CoBots and their shortfalls. Presented thereafter is a discussion on DTs and the generic DT architecture on which the proposed DT solution is based. Finally, the aggregated DT solution for HRC is presented, along with discussions on the functionality of each DT involved.

2 Human-Robot Collaboration

2.1 Classification of HRC

The HRC research field is focused on finding solutions to problems involved in enabling a human and robot to work together to achieve a common goal. Research into HRC is motivated by the desire to achieve high levels of manufacturing flexibility [5]. As shown in Table 1 and Fig. 1, HRC applications can be divided into categories according to the level of collaboration between the robot and human. In Fig. 1 the orange zone represents the human operators' workspace; the green zone represents the robot's workspace; and the overlapping zone represents the shared workspace.

Although there have been significant advances in manufacturing HRC, most collaborative applications today are constrained to level two and level three collaboration.

Table 1. Levels of HRC (*adapted from* [4, 6])

Level of collaboration	Same vicinity	Shared workspace	Shared time	Shared workpiece
1. Cell (fenced robot)				
2. Coexistence	x			
3. Sequential collaboration	x	x		
4. Co-operation	x	x	x	
5. Responsive collaboration	x	x	x	x

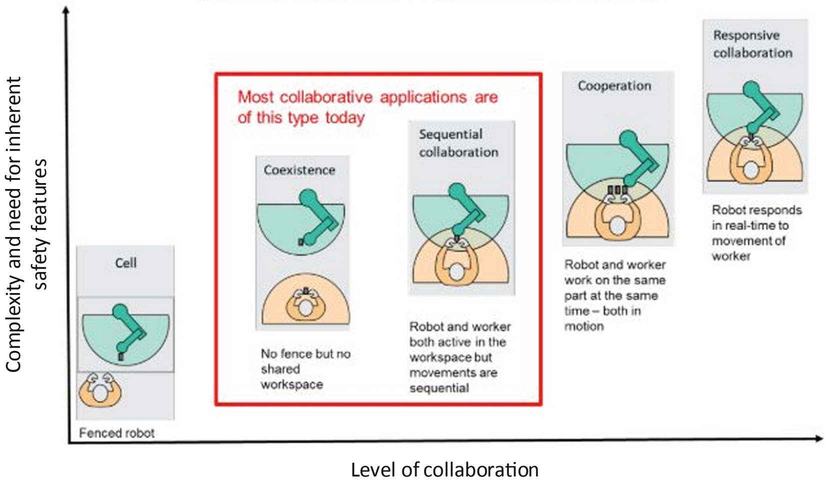

Fig. 1. Types of HRC (*adapted from* [4, 6])

Actually, many robotic applications are still at level one, where the robot and human are separated by the fence while the robot is functional. To achieve level four and level five collaboration, more advanced technologies are required, which enable intelligent control of the robot. Many of the challenges involved in HRC become evident when trying to achieve these levels of collaboration.

2.2 Challenges Associated with Human-Robot Collaboration

The challenges faced in high levels of HRC require interdisciplinary solutions, often involving a combination of classical robotics, artificial intelligence, cognitive sciences and psychology [3]. These are some of the challenges identified with regard to successful implementation of human-robot collaborative workstations:

- **Ensuring that the collaborative workstation is safe:** Safety considerations are crucial in collaborative workstations, where humans and robots work in close proximity.

It should be the first consideration when designing tasks for HRC. More research is needed in order to enable safe and robust robot action - especially in environments where unforeseen events are possible [7–9].

- **Robotic interaction in the presence of uncertainty:** For a robot to successfully participate in an interaction with a human, it is necessary to obtain a thorough understanding of the environment and the interaction dynamics. This includes knowledge of the partnering agent, its internal state and the constraints that are imposed on the object with which interaction needs to occur. Accurate models are necessary for capturing the interaction dynamics [1, 8].
- **Motion planning and control needs to occur in near real time to ensure natural workflow:** In an interactive setting, it is necessary to be able to instantaneously generate control commands so that the robots' actions meet the user requirements. Classical *sense – plan – act* architectures are not sufficient [1].
- **Effective use of multisensory data in real time is necessary:** Many existing methods for integrating sensor data are not adequate for accurately capturing the dynamics of physical contact with rigid and deformable objects [1].
- **Communication mediums, such as speech, gaze and gestures need to be unambiguous and interpretable by the robot controller algorithms:** Both parties must be able to convey instructions between each other and should be capable of referring to objects in a shared workspace without confusion [1].
- **Reproducing the effectiveness and flexibility of human hands remains an open challenge:** Robotic grippers still lack dexterity when compared to human hands [1].

CoBots are becoming prevalent in industry today and they bring solutions to a few of the problems listed above. The foundation of collaborative robots is based on solving the most important concern in HRC - safety. However, these safety improvements come at a cost - limited payload size and limited speed of operation, and therefore limited throughput. This cost is currently quite prohibitive and limits the use of CoBots to simple automation tasks.

Cobots rely heavily on safety stops initiated on impact. Once a robot encounters a safety stop the operator usually needs to intervene to get the robot functional again. Safety stops disrupt natural workflow and throughput in a collaborative workstation, where obstructions can occur within the programmed robot path at any time.

Without augmenting CoBot capabilities, they currently cannot be used to achieve high levels of collaboration, since they simply do not address enough of the challenges in HRC implementation. They do however provide a good starting point by incorporating necessary safety features to ensure that injury/damage is minimized if impact does occur. By developing a means to intelligently control the collaborative robot in real-time, it is possible to exploit the benefits that these robots bring, while increasing their efficiency, effectiveness and range of applicability.

2.3 Collaborative Robot Applications

Collaborative robots provide small and medium-sized enterprises (SMEs) with a viable entry-point to robotic automation, allowing them to benefit from the quality and productivity improvements that come with robotic automation. However, CoBots are not limited to SMEs; they can also offer productivity and ergonomic improvements for larger enterprises that already have automated production lines. Applications of CoBots include: assisting to carry heavy tools, fetching parts, feeding machines and performing quality inspections [4].

Human-robot collaboration has been identified to be best suited to manufacturing operations involving high product variance and low production volume [10]. As shown in Fig. 2, CoBots fill the gap between manual assembly, and robotic automation [10].

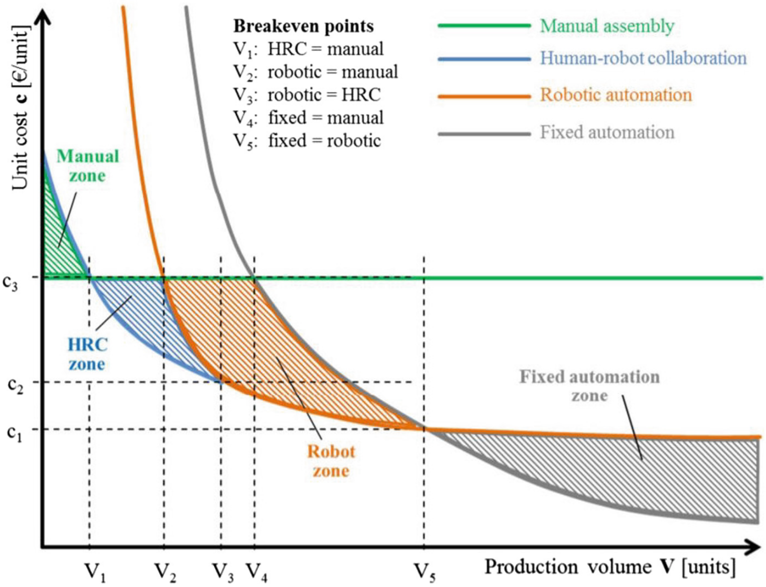

Fig. 2. Economically justified operational regions for manual assembly, HRC, robotic automation and fixed automation [11]

3 Digital Twin Architecture

One of the concepts growing in popularity as an Industry 4.0 driver is the DT. A DT is defined in [12] as a “multiphysics, multiscale, probabilistic simulation” of a system, that utilizes the most accurate physical models and sensory data to mirror the life of the physical entity which it attempts to ‘twin’; i.e. DTs gather real-time sensor data from multiple entities and effectively aggregate the data to produce a digital replica of the physical entities.

The primary goal of DTs in the manufacturing industry is to optimize the entire production system by enabling the real-time integration of simulation data and sensory data [6]. This integration opens the door to real-time monitoring and re-planning of production activities to ensure that actions performed are always the most efficient ones from a business and operation perspective. Using DTs, complex problems can be solved through *sense - predict/perceive - plan - act* architectures, over *sense - plan - act* architectures. Some of the roles of DTs presented in literature include: remote monitoring, predictive analytics, simulating future behaviour, optimization and validation [13].

A reference architecture for a single DT instance, called the Six-Layer Architecture for Digital Twins (SLADT), has been proposed in [13]. This architecture has been expanded in [14] to accommodate the aggregation of multiple DT instances. This expanded architecture is called the Six-Layer Architecture for Digital Twins with Aggregation (SLADTA). SLADT and SLADTA are illustrated in Fig. 3. The various layers of SLADT are characterized as follows [13]:

- **Layer 1 and Layer 2:** The physical twin is encompassed in these two layers. It consists of the entire physical twin, along with the various sensors and data sources which measure and provide the actual state of the physical twin to the higher levels.
- **Layer 3:** This layer consists of the local data repositories such as databases, stored near the physical twin. It is recommended that vendor neutral data servers communicating through secure, reliable and widely used communication protocols, such as OPC UA, be used. The data servers should also be able to communicate with an IoT gateway, or directly with the cloud if applicable.
- **Layer 4:** This layer is an IoT gateway, which serves to convert data into information before uploading it to cloud services. It also serves to manage communication between the cloud and the local data repositories, and between DTs.
- **Layer 5:** This layer represents cloud-based information repositories which serve to enhance availability, connectedness and accessibility of the DT.
- **Layer 6:** This is an emulation and simulation environment which adds intelligence to the DT. The actual functionality of this layer depends on the use-case. This layer is connected to the local data repositories and cloud-based information repositories.

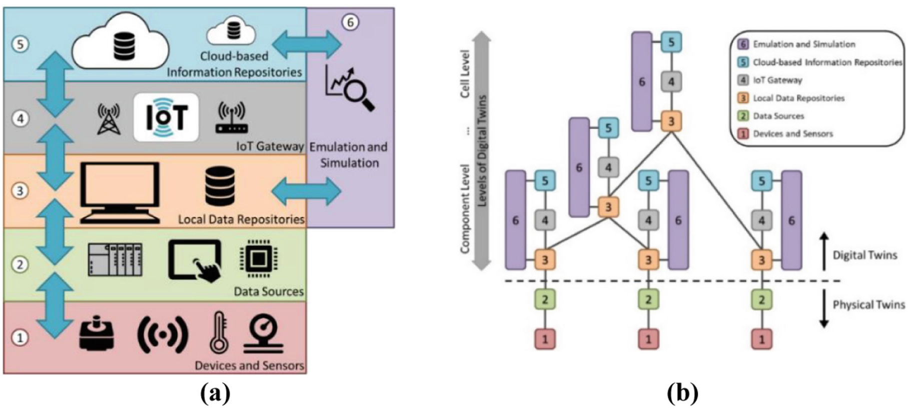

Fig. 3. (a) Six-Layer Architecture for Digital Twins, (b) Six-Layer Architecture for Digital Twins with Aggregation [14]

SLADTA, shown in Fig. 3b, aims to enable the creation of DTs of multi-system environments through the aggregation of information from various DTs. This is particularly beneficial when the system to be twinned is composed of many different components, possibly from different manufacturers. Methods and protocols for communication between the various DTs are presented in [14]. The key SLADT layers involved in aggregation are levels three and four. The DTs are connected with one another in a hierarchal manner through their level three or level four, and OPC UA is suggested for implementing these connections. The flow of information between the DTs is controlled in layer four (a custom-built IoT gateway).

The benefit of utilizing an aggregated DT model is that data is reduced as it travels up towards the higher-level DTs. This ensures that only valuable information arrives at the highest DT levels where value-creating decisions are made based on the goal of the whole system. Some other key benefits of DT aggregation are [13]:

- **Segmentation of information** – Components from different manufacturers can be used without necessitating the breach of data confidentiality.
- **Reduced complexity** – a potentially large DT can be broken down into several smaller DTs with encapsulated functionality and information. Each DT can then be flexible with respect to its internal architecture and can make decisions by itself without the need for much data interchange. This reduces the overall complexity of data management.

4 A Digital Twin Architecture for Human-Robot Collaboration

4.1 Architecture Overview

To achieve efficient co-operative and responsive collaboration (see Fig. 1), it is necessary that each entity involved in collaboration is aware of the intentions and state of each of the other entities [3]. In this way, all entities will be working towards a shared plan to achieve the common goal [3]. Therefore, a robot involved in collaboration needs to have the ability to perceive and comprehend its environment, so that it can plan, learn and reflect [3].

By aggregating the DTs of all entities in a collaborative workstation, it is possible to centralize and analyze information about all entities with respect to the common intention. This aggregation of DTs can then be used as a basis for intelligently controlling the robot and informing the human operator of upcoming robot operations.

It is believed that through intelligent control it is possible to increase throughput in collaborative robot applications by: reducing stoppages due to impact; increasing collaborative robot motion speed whenever safe to do so; and changing the production plan without direct physical human intervention. This idea is supported by [15], where an active collision-avoidance system driven by vision sensors was developed with the aim of providing better flexibility and productivity in a collaborative robot application.

Figure 4 illustrates the DT architecture for HRC that is proposed in this paper. The DT will be used to capture the state of critical entities in a collaborative work cell, such that future states can be predicted, and robot control commands can be adapted to optimize parameters such as safety, throughput and energy consumption.

The architecture is based on SLADTA. This choice is motivated by the benefits of DT aggregation for realizing the DT of a multi-system environment (see Sect. 3).

The architecture proposes the formation of a collaborative work cell DT through the aggregation of the DTs of all entities in the work cell. The basic DTs required are: the collaborative robot DT, the human operator DT and the workspace DT. Any other active and intelligent components that form part of collaboration should have a DT of its own and form part of the aggregation. To reduce latencies, it should always be attempted to minimize data transfer between the DTs; therefore, each individual DT should act as independently and intelligently as possible such that only real value-adding information is passed to higher level DTs. The highest level is the collaborative work cell DT, where business and operation critical decisions will be made.

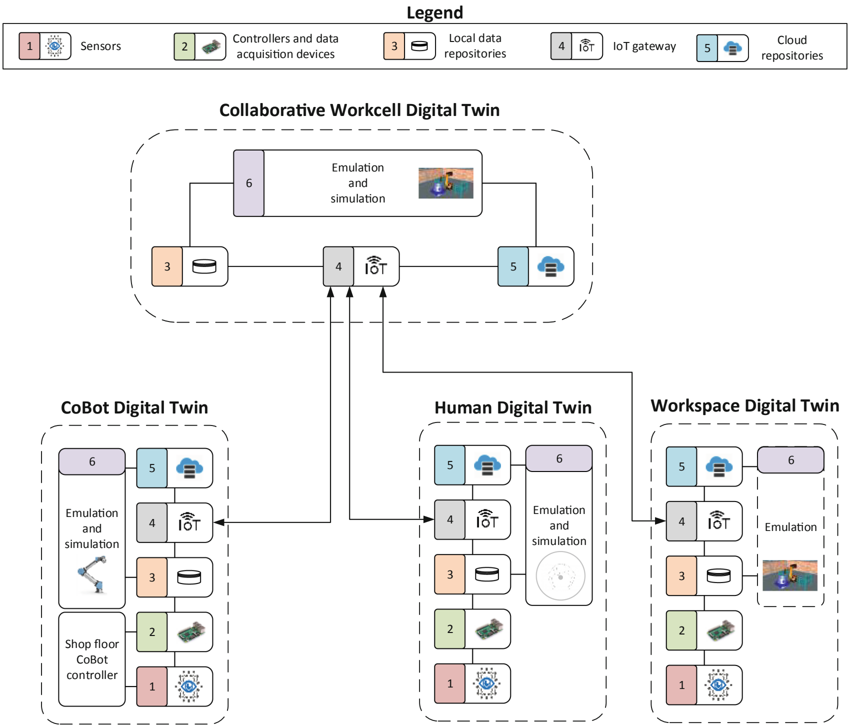

Fig. 4. DT architecture for HRC

Collaborative robots aim to introduce flexibility to production systems by achieving fast and simple changeover between robot tasks and operations. To achieve this fast changeover, CoBots typically allow for programming through demonstration. On this premise, the DT will only be expected to exert control over the robot if an undesirable event, e.g., the movement of the robot in the collision path of another entity is detected.

The robot DT will be responsible for executing adaptive control and motion planning of the CoBot, on instruction from the collaborative work cell DT. This is one of the most critical functions of the entire DT solution and it always involves high frequency data streaming from the CoBot. Motion planning could also be done by the collaborative work cell DT, it might be preferred since it contains information about the entire work cell. However, to ensure proper encapsulation of data specific to the CoBot, it is suggested that robot motion planning remains a function of the robot DT; while information such as safe-zones for motion are obtained from the collaborative work cell DT.

4.2 Human Digital Twin

In [16], the concept of a human DT has been explored and its importance in Industry 4.0 environments has been established. Key findings were that a human DT needs to utilize modern human-machine interfaces and behavioural modelling to enable the storage and communication of relevant information about the human to the entities that are associated with the human within the work cell. The Holonic Manufacturing System approach was identified as a suitable approach for developing a human DT.

The primary goal of the human DT is to always provide an as accurate as possible state of a human operator in the collaborative work cell. The human operator state includes information about the operators' pose, position, current activity and future activities. This allows the robot to have insight into the operators' activities and goals.

Accurately capturing the dynamics of a human being in a work cell is complex task; however, advances in vision technologies and reduction in sensor sizes, make this increasingly possible. Researchers have shown that it is possible to accurately track:

- The human body and actions in 3D through commercial motion capture devices such as the Microsoft Kinect depth camera [15, 17];
- 3D location of a human in a workspace through RFID [18];
- Human eye gaze and target using commercial eye trackers such as Tobii X2-30 [19];

Open source algorithms, such as the following, are also readily available today: BlazePalm [20] for real-time hand/palm tracking and gesture recognition, and PoseNet [21] for estimating the pose of a human in an image or video.

Level one of the proposed human DT (see Fig. 4) is composed of the sensors necessary to track the human operators pose, position and heading in the work cell. The primary sensor is a camera array that can be shared between the human DT and the workspace DT. The raw data is gathered by the data acquisition device in level two. The raw data is analysed using algorithms in layer six to determine various types of information about the human, such as the predicted path of motion with confidence levels.

4.3 Workspace Digital Twin

The primary goal of the workspace DT is to monitor and track any changes in the collaborative workstation that is otherwise untracked by any other DT. The core information held by this DT can be a 3D representation of the static and dynamic work environment. This 3D representation will be used by the collaborative work cell DT to determine obstruction-free areas in the workspace that the robot may be able to move through. This information is crucial to enable motion planning and in-situ adaptive control of the robot in changing environments. The 3D representation of the environment can be in the form of a depth map. Fine details of the environment may not be of importance. To reduce computation time workspace change detection should be employed instead of constantly re-computing the entire workspace map.

It is evident from literature that camera-based monitoring is a popular method for monitoring shared workspaces. Some ways to achieve a 3D representation of a workspace is through the use of a set of stereo vision cameras [22]; depth cameras, such as a Microsoft Kinect [23] or through the combination of sensor data from multiple 3D sensors of different modalities [24].

One interesting idea for developing the 3D map described previously is to start with a 3D CAD model of the collaborative workstation - which represents most of the components in the workspace - and then complete the model using data from a stereo vision camera array, by dynamically mapping any additions and changes in the environment.

Layer one of the proposed workspace DT (see Fig. 4) is composed of the sensors necessary to detect the state of the static and dynamic work environment. The primary sensor is a camera array that is shared between the human DT and the workspace DT. To improve confidence in the camera data, extra sensors can also be employed; for instance, to track continuously moving objects in the workspace, such as objects on a conveyor belt. The raw data is gathered by the data acquisition device in layer two. Algorithms in layer six use the raw data from the various sensors to create the required workspace map.

4.4 Collaborative Robot Digital Twin

One goal of the CoBot DT is to acquire the actual state of the robot (including the associated end effector) and make this information available to other DTs. It will also serve the crucial role of adapting the control of the robot on notification from the collaborative work cell DT. This is expected to occur mainly when: some unsafe condition has been detected; a more optimal control plan has been established; or when a new task has been assigned to the robot. The manner in which the control is adapted will depend on the information sent to it from the collaborative work cell DT.

Layer one of the proposed CoBot DT (see Fig. 4) consists of all sensors required to obtain information regarding the complete actual state of the robot. This information includes robot pose, power consumption, torque at each joint and end effector state. Most collaborative robots come with built-in sensors that provide all the necessary information about the robot state. Collaborative robots such as the Universal Robot UR5e also allow the end effector to be controlled and monitored by the CoBot controller. All sensor information can therefore be obtained by interfacing with the robot controller.

Layer two of the CoBot DT consists of the CoBot controller. Any other devices required to enable communication between the CoBot controller and the local data repositories (3rd layer) are also part of this layer. Historic data about the robot state can be stored in cloud repositories (5th layer) or in a local data repository if often accessed.

The CoBot DT is the best source for data regarding the CoBot and its actual state. Layer six provides the CoBot DT the ability to use this data - along with information provided to it by the other DTs - to run simulations to investigate and optimize the tasks it needs to perform. These tasks could include motion planning, power optimization and payload gripping location determination.

4.5 Collaborative Work Cell Digital Twin

This is the highest-level DT, formed by the aggregation of the collaborative robot DT, the human DT and the workspace DT. It contains (or has access to) all the information necessary to make business and operation critical decisions. This makes any visualization of the system information best done within this DT.

The primary goal of this DT is to monitor and identify any unsafe or suboptimal conditions in the work cell from a business and operation level, and then to inform DTs controlling the affected process of any changes required to ensure conditions are optimal. These decisions are made through simulations in layer six which can provide the needed capabilities using software such as Siemens Technomatix, Simio or AnyLogic.

In the task planning stage, simulations can be used for path, activity, and workspace planning to optimize parameters such as power consumption, human and robot motion distances. Once optimal parameters have been obtained, the robot can be programmed to comply with these parameters. Once the robot program is live, the collaborative work cell DT will be continuously updated with the state of the robot, human and workspace through their respective DTs. Within layer six, this real-time information can be used in various ways, for instance to calculate the safe zone for robot motion in the form of a free-space map, i.e. a model indicating the space within the work cell which is unoccupied by any other entity and is available for the robot to safely navigate through.

The free-space map can then be used to consistently check that the robot is not currently moving, and in the near future is not expected to move within any unsafe zone. If otherwise detected, the collaborative work cell DT informs the CoBot DT to generate a new robot motion path within the safe zone. If the time to collision is less than that to generate a new motion path, the CoBot DT is informed to stop until some condition is met or to move to a safe position till the original path is clear. The work cell DT can be used to inform the operator of the robot's intended motion and possible collisions.

5 Conclusion and Future Work

CoBots offer solutions to some of the challenges associated with HRC. However, the improvements they bring come at a cost; one cost is throughput. A DT solution has the potential to address some of the shortfalls of CoBots by enabling intelligent control of the CoBot and the collaborative work cell.

This paper first establishes the need for intelligent control of a CoBot, and then presents a DT solution for enabling its intelligent adaptive control. The primary goal of the DT is to improve CoBots' safety, efficiency and effectiveness. The proposed architecture aggregates: a collaborative robot DT, a human operator DT, and a workspace DT. The value to be produced by each DT, as well as possible technologies that can be used to create each DT, are also briefly discussed. Future work involves a detailed requirements analysis for each DT, followed by the implementation of the proposed DT solution in an industrial case study, that will be used to evaluate the performance of the DT solution relative to improve safety, throughput and efficiency of the collaborative robot.

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