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The Need for a Symbiotic Interface for a Digital Twin

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Abstract. Human interaction with a Digital Twin is an emerging concept for which there are no common definitions. This paper considers the various types of human interaction with Digital Twins. There is very little research considering human cognitive interaction with a digital twin, therefore to enable human and digital twin interactive collaboration an interface is required. In a dynamically changing environment there is a need for an intelligent adaptive user interface which adapts to the context and to the skills, requirements and preferences of the human operator. This type of interface, which is termed a "symbiotic interface", needs to learn, evolve and to provide support for decision making, problem solving and unanticipated events. Ecological interface design (EID) is identified as a suitable design methodology to create this interface.

Keywords. Digital Twin, Ecological Interface Design, Intelligent Adaptive Interface, Human Interaction, Decision-making

Introduction

The concept of a Digital Twin was first introduced by Grieves in 2003 in a course on "Product Lifecycle Management [1]. Grieves [1] defined a Digital Twin as consisting of three main parts: products in the real world; products in a virtual world and the data connection linking the virtual and real products. Comprehensive literature reviews of Digital Twins have been presented by Semeraro et al. [2] who reviewed 150 papers and Tao et al [3] who reviewed 100 papers. Both papers commented on the need for a unified reference model. Semeraro et al. [2] found that human-Digital Twin interaction is a key challenge in the development and implementation of Digital Twins in the manufacturing sector.

Grieves [1] stated "The digital twin capability supports three of the most powerful tools in the human knowledge tool kit. These three tools are: conceptualization, comparison, and collaboration. Taken together, these attributes form the foundation for the next generation of problem solving and innovation". Over the subsequent years many definitions of Digital Twins have evolved and the human knowledge element seems to have been lost. For example the draft standard ISO/IEC 30173 ED1: Digital Twin - Concepts and terminology [4] defines a digital twin as a "digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization".

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Very few studies exist on human-Digital Twin interaction [5]. However, the Digital World 2050 Report [6] states that human observation will increase in importance with the growth in digitisation to supervise critical information flows and will remain an active participant in the provision of next generation production systems. An existing review within this novel field is that of Wilhelm et al. [7] who have conducted a scoping review considering implementations of Digital Twin-based Human-Machine Interaction in production and manufacturing, analysing 23 papers published in the time span 2016–2020. Wilhelm et al. [7] consider scenarios applying Digital Twin-based Human-Machine Interaction and have identified four main areas: (i) Production Planning and Production; ii) Maintenance, in which the operator is supported in their work activity; (iii) Teleoperation, where the operator is in control of the Digital Twin and has powers of decision-making; (iv) Collaborative Robotics, where the operator interacts with the Digital Twin instead of being in direct control of the robot.

This paper will consider Human and Digital Twin Interaction from the point of view of types of cognitive interactions and support. The need for a human-Digital Twin interface is identified and the features required by such as interface are discussed. Digital Twins are categorised within this paper as complex sociotechnical systems. Ecological interface design (EID), which is a theoretical framework for interface design for complex sociotechnical systems [8], is introduced. The paper concludes by identifying Ecological interface design (EID) as a methodology suitable for Digital Twin interfaces.

1. Human and Digital Twin Cognitive Interaction

Human interaction with a Digital Twin is an emerging concept for which there are no common definitions. There is very little research considering human cognitive interaction with a digital twin. This concept is currently comprised of the following subject areas:

- Cognitive Digital Twin
- Augmented reality assisted Digital Twin
- Digital twin of a human
- Human-machine interaction
- Human-in–the-loop
- OPERATOR 4.0

This section will review the research occurring within each of these areas and consider how they relate to each other. It should be noted that the last three subject areas (Human-machine interaction, Human-in–the-loop and OPERATOR 4.0) are not specific to human-Digital Twin interaction but apply more widely to cognitive interactions between humans and digital systems. Digital systems communicate information in electronic forms. A need for an additional research area to consider human-Digital Twin information exchange is identified.

A Cognitive Digital Twin is an emerging concept with no widely accepted definition [2]. The key additional capabilities which make a Digital Twin a Cognitive Digital Twin are defined by Al Faruque et al. [9] as:

- “perception (forming useful representations of data related to the physical twin and its physical environment),

- attention (focusing selectively on a task or a goal or certain sensory information either by intent or driven by environmental signals and circumstances),
- memory (encoding information, storing and maintaining information and retrieving information),
- reasoning (drawing conclusions consistent with a starting point),
- problem-solving (finding a solution for a given problem or achieving a given goal),
- learning (transforming experience of the physical twin into reusable knowledge for a new experience)" [10].

Zheng, Lu and Kiriitsis [10] added the capability sensing complex and unpredicted behaviours and extend the reasoning capability to include enabling optimisation strategies for continuously evolving systems. The augmented cognitive capabilities are provided through cloud-managed artificial intelligence (AI), machine learning (ML) services [11] and semantic technologies such as ontology and knowledge graphs [10]. It should be noted that a Cognitive Digital Twin attempts to replace or mimic human input and does not consider human interaction with the Digital Twin. It is included in this review as it models human cognition. Fernanadez et al. [12] introduced the novel concept of an Associative Cognitive Digital Twin which is a digital expert or copilot which can learn and evolve, and that integrates contextual information for the desired goal. The Associative Cognitive Digital Twin framework uses both human and machine "mental" models to enable human-machine communication, cooperation, understanding and empathy. The machine mental model is implemented via a graph database.

Augmented Reality (AR) uses images and text to enhance the real-world, via devices such as smartphones, tablets and AR glasses (e.g. Hololens) [13]. Yin et al. [14] observe that AR is fundamentally a human-centric technology, providing bi-directional information transmission transparency and enabling more efficient working practices. Yin et al. [14] reviewed 118 publications on AR-assisted Digital Twins which they structured according to the engineering lifecycle of design, production, distribution, maintenance and end-of-life. They found that in the product design field Digital Twins could simulate and predict the product state which could be better visualised by designers using AR. In the service design domain AR-assisted Digital Twins provide context-aware and on-site training for users with step-by-step guidance. Digital Twins can monitor and analyse real-time data of vehicle systems or energy management and assist city managers in decision-making and feedback control.

At the production stage AR-assisted Digital Twins can be used for collision detection in operation planning and future failure can be predicted by the Digital Twin, whilst AR can give hazard warnings to the operator through visual or sound information. During monitoring and control a virtual machining process based on real-time data can be visualised in a dry run. Assembly AR-assisted Digital Twins can provide context-aware assistance in assembly. When robotics are used to assist production, AR-assisted Digital Twins can enable robots to be equipped with higher-level cognitive capabilities, i.e. the use of the AR wearable end computational unit allows a Cognitive Digital Twin (described earlier) to be created. For example, the operator can adjust the robot position via gesture-based interaction with the robot's Digital Twin, aiding the robot DT to how learn to move more accurately.

In the distribution phase Yin et al. [14] found that case studies have verified the potential value of AR-assisted Digital Twins in data management, navigation, and vision picking assisting in warehouses. At the maintenance stage the user of AR with a Digital Twin was able to integrate procedures encompassing fault prediction and warnings, on-site inspection, maintenance guidance, annotating and updating data and remote collaboration. Yin et al. [14] only found one paper which considered the end-of-life phase. An AR-assisted Digital Twin was applied to radioactive waste safety management to secure human operator safety. Yin et al. [14] conclude that for AR-assisted Digital Twins the discovery of actual needs, innovation of interactive approaches, and development of human-centric workflows require further investigation. This holds true for all human and Digital Twins interactions.

A Digital Twin of a human models human abilities, characteristics and preferences with the aim of providing personalised information [15]. Three specific examples exist of this in the literature [15,16,17]. Siemens have patented a human-programming interface (HPI) that facilitates human-machine interaction and the interpretation of human behaviour. A digital twin for each worker is generated and updated with current data for the worker. Access to the digital twin is provided via an HPI. The HPI provides information on worker skillsets, availability, and capability based on biological information. The HPI can also be used to provide workers with instructions [16]. Josifovska et al. [15] described two applications of a human Digital Twin in the context of user interfaces for manufacturing assistance systems: (1) manual assembly of E-Cabinet and (2) manual assembly of a product in a smart factory. Josifovska et al. [15] observed that one of the challenges in developing of smart assistance systems was the need to obtain knowledge about the workers' personal characteristics (e.g., age, vision impairments, cognitive capabilities, etc.) and past user experiences (e.g., usage of certain devices, apps, interaction styles etc.). Locklin et al. [17] presented a Human-centered Digital Twin (H-DT) architecture to model production operators. Locklin et al. [17] considered the issue of privacy of individual data. The H-DT is able to anonymise data by to representing a specific operator role instead of an individual. As the Digital Twin of a human contains cognitive information it can be seen that there is overlap between this term and a Cognitive Digital Twin.

Ma et al. [18] state that the purpose of Human-Machine interaction is to combine "human intelligence, skills and adaptation with the machine repeatability, precision and predictability". The main HMI technologies include Virtual Reality (VR), Augmented Reality (AR), haptic interaction (movement or touch interaction), voice recognition and gesture recognition. They surveyed the use of HMI in the product lifecycle noting that HMI can be used in design and training through the use of AR and VR. However, they also included the use of physical interaction by describing research in human-robot collaboration which does not fit their definition. Ma et al. [18] discovered that a Digital Twin provides an opportunity to enhance HMI by offering more comprehensive information to users. They concluded that research into HMI and Digital Twins is in its infancy and needs more work is needed to understand how these technologies can be integrated.

The phrase "Human-in–the-loop" "refers to a model that requires human interaction either to make human decisions more efficient and accurate, to make machine learning models more accurate, when the risk of prediction error is too high, or when the training data is rare or not available" [6]. In effect this means humans are being guided by machine learning results or human experience and judgement is used to modify the result of machine learning. This model is starting to be applied to Digital Twins [19, 20, 21, 22]. All these papers consider the use of either AR or VR interfaces. "VR refers to the complete immersion of the user in a 3D digital environment using a head-mounted display such as the Oculus Quest or Vive Index"[13]. Yigitbas et al. [21] identified two important challenges in human-computer interaction: transparency and controllability.

Transparency requires user understanding. To preserve the user's trust and provide spatial awareness, the user needs to be given feedback, explanations and pictures of the state of the system in context. However, representing the system and its context is complex. Mechanisms should be provided to allow the degree of controllability to be adjusted according to circumstances (e.g., changing goals, emergent behaviour, uncertainties, or user preference). Human input into decision-making and adaptation processes within the Digital Twin should be supported in a natural and interactive way.

OPERATOR 4.0 is defined as a smart, skilled operator who works cooperatively with robots and also aids machine work "by means of human cyber-physical systems, advanced human-machine interaction technologies and adaptive automation in order to achieve a a human-automation symbiosis work systems" [23]. Cyber-Physical Systems (CPS) are intelligent systems that integrate hardware with communication, computational and control capabilities [24]. Peruzzini et al. [25] define a theoretical human-centred framework for Operator 4.0 based on the study of human activities and behaviours within the smart factory. The Smarter Operator concept from OPERATOR 4.0 comprises the operator's cognitive capability needed for the job and under certain operational setting. Due to the upsurge in the need for flexibility and adaptability of production systems there is a need for cognitive aids to be developed that help the operator, such as those provided by augmented reality (AR) technologies or 'intelligent' Human-Machine Interfaces (HMI) to support the new/increased cognitive workload (e.g. situational awareness, decision-making, diagnosis, planning, etc.) of OPERATOR 4.0. Tools which unobtrusively identify when assistance is required comprise cognitive tests to match the abilities of the operator with the skills needed for performing a job and machine learning tools to measure and dynamically diagnosis a real-time operator's cognitive performance [26].

None of these technologies specifically consider the role of the human within the Digital Twin, how to present the information needed to support the human in carrying out the role tasks or how to enable the human to communicate with the Digital Twin. Associative Digital Twins work with a user but do not consider how to display the exchange of information with the user. AR-assisted Digital Twins provide a method of communication with the human but do not consider the role of the human within the Digital Twin. To enable human and Digital Twin interactive collaboration an interface is required. This interaction can be made more user-friendly using smart interfaces which adapt to user requirements, skills and preferences and to the overall system context. A symbiotic relationship is one "involving people or organizations that depend on each other equally" [27]. Hence a symbiotic interface is defined here as an interface which considers the mutual interaction between people and systems that depend on each other equally. The interface will facilitate the exchange of information between humans and a Digital Twin to enable co-working towards achieving the goals of the system. The focus is on what information to display to the user, rather than on how to display it.

Figure 1 (below) shows the current research fields applicable to human cognitive interactions with a Digital Twin, plus the new field of "symbiotic interface" proposed, and the technologies employed to aid cognitive interaction. It can be seen that although these research fields comprise discrete subject areas there are several overlaps, with several fields making use of AR technologies and AI cognitive capabilities such as machine learning. Currently most research within the emerging field of human Digital Twin cognitive interaction is taking place in the area of AR-assisted Digital Twins. It can be envisaged that in the future more consideration will be given to Digital Twins in the "Human-machine interaction" and "Human-in-the-loop" research fields.

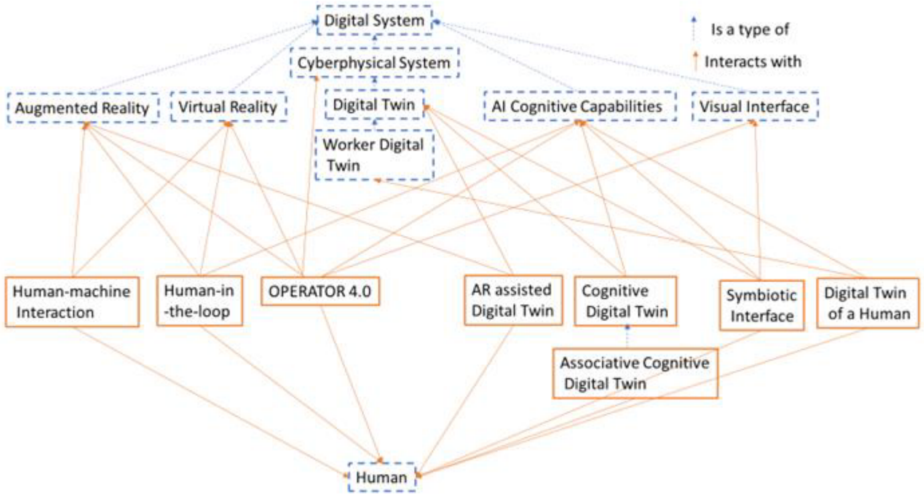

Figure 1. Research Fields considering Human and Digital Twin Cognitive Interaction.

The section above has identified that more work is needed to consider human-Digital Twin interaction and to gain more understanding of human-centric workflows. Interaction can be either one-directional whereby the user is supplied with extra information by the Digital Twin (e.g., decision-making support based on simulations or maintenance instructions) or bidirectional when both the user and Digital Twin react to new input (e.g., control) [28]. Wang and Canedo [16] note that in future smart factories the role of humans will be increased as they will become the critical decision makers, cooperating with machines to achieve unparalleled levels of efficiency and creativity. To achieve this for smart factories the machine-to-human interface to needs to be clearly defined, for example to: facilitate human supervision of machines; enable human-decision making where machines are unable to; allow exchange of tasks with machines; and optimise production via machine analytics.

2. Symbiotic Interface Features Required

The previous section described the need for an interface to facilitate human and Digital Twin interaction. The requirements for an interface which enables interaction will now be considered.

Jones et al. [29] define four basic properties for a human-machine interface:

1. To capture and display events and sequences – Transition-focussed.
2. To reveal what should/can happen next – Future-focussed.
3. To support quick recognition of unexpected or abnormal conditions – Pattern-focussed.
4. To capture the state and trends in higher order system properties – Abstract-focussed.

Jones et al. [29] state that the interface must support the human in constructing an accurate model of the real-world problem and allow the human to correct the problem based on this model. As mentioned by Yigitbas et al. [20], human input into decision-making within a Digital Twin should be supported in a natural and interactive way.

Further features needed by a symbiotic interface to support the cognitive workload recognised by OPERATOR 4.0 are:

- An explanation feature;
- To display information within context;
- The ability to adapt to user type;
- To ability to adapt to user preference;

To engender trust humans need to be provided with explanations in order to understand the rationale behind a Digital Twin's decision-making logic and it's applicability within a given context [30]. Different system contexts (e.g., steady state conditions, fault diagnosis, process stage) will require the display of different information. For example, more information could be displayed about a system element which has entered an error state. Context also dictates the level of detail to be displayed. For example, an annual maintenance review will abstract the appropriate information from hourly system logs. Relevant information will be shown to a user at the appropriate time, avoiding information overload.

Different user types will require different kinds of information to be provided or emphasised. For example, novice users will require a greater depth of information to be provided than experienced users. Company accountants will wish to focus on cost information within the digital model, whereas technical managers will be concerned with usage statistics.

Each user will have a preference on how to interact with the interface. A user may prefer information to be presented graphically or in a text format, or a certain view of the information. The interface may 'suggest' possible inputs to the current user based on the user's interaction history with the system. Every user will have unique expectations on how the system functions based on individual past experience with similar systems. Therefore, the interface will need to adapt to provide each user with their expectation of how the system should behave.

3. Digital Twins as Complex Sociotechnical Systems

Digital Twins are complex systems as suggested by the title of the paper "Taming the Complexity of Digital Twins" [31]. Atkinson and Kuhne [31] stated Digital Twins combine multiple, diverse technologies used in the engineering and operation of complex systems throughout the lifecycle. This view is echoed by Tao et al. [32] who spoke of the need of for multiple physical entities within a Digital Twin to communicate and collaborate with each other to perform a complex task which is beyond the performance of any individual device. Tao et al. [3] also described the need for multiple virtual models to interact and collaborate, connecting to form a network for information sharing. One of the research challenges in Digital Twin implementation, identified by Semeraro et al. [2], is that the Digital Twin comprises a set of models with complex structures and behaviour, reflecting the real-time operations of the physical system. In addition, Semeraro et al. [2] noted a Digital Twin is often applied to environments typified by uncertainty, where both external and internal factors may cause operational conditions to vary.

The authors of this paper argue that in addition to being a complex system a Digital Twin is also a sociotechnical system as any system interacting with both a human element and enterprise comprises a sociotechnical system. The Oxford Dictionary of

Construction, Surveying and Civil Engineering defines a sociotechnical system is "system that appreciates the interaction of people and technology in a workplace setting" [32]. The ability of humans to act as information sensors, providers of knowledge, decision makers and supervisors renders them an essential component of a Digital Twin. As with any other system a Digital Twin is embedded within an enterprise system which must be referenced to explain the purpose of the Digital Twin [33].

EID is an obvious candidate for designing interfaces for complex human-machine systems where unanticipated events can occur [34] such as in Digital Twins. EID considers the work domain rather than specific user tasks, using multi-level analysis to support problem-solving and visualising domain constraints within the interface. Traditional user-centred design approaches are unable to capture the complexity inherent in Digital Twins [35]. Other than EID, there are hardly any frameworks in the literature enabling the design of engineering interfaces which provide cognitive support and worker adaptation [36].

4. Conclusion

Types of human cognitive interaction with a Digital Twin have been considered. More work is needed to investigate this type of interaction with Digital Twins and the workflows which occur when humans and Digital Twins collaborate to undertake system tasks and decision-making. Digital Twins have been categorised as complex sociotechnical systems. The need to consider an interface to enable human-Digital Twin interactive collaboration interface has been propounded. This type of interface, which has been termed a "symbiotic interface", needs to learn, evolve and to provide support for decision making, problem solving and unanticipated events. Support is necessary to design and create such an advanced interface. The authors believe that the Ecological Interface Design approach (EID) is a suitable methodology.

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