Abstract—The next revolution of industry will turn the industries as well as the entire society into a human-centric shape. The presence and impacts of human beings in industrial systems and processes will be magnified more than ever before. To cope with the emerging challenges raised by this revolution, 6G will massively deploy digital twins to merge the cyber-physical-human worlds; novel solutions for multi-sensory human-machine interfaces will play a key role in this strategy.

Index Terms—Digital twins, 6G, Industry 4.0, HMI

I. INTRODUCTION

The concept of digital twin (DT) has been attracting profound attentions recently. It was first coined in 2014 in the context of manufactory to denote a virtual equivalent that models a physical product [1]. Triggered by the vigorous development of Internet-of-Things (IoT) and cloud computing technologies, the concept has been widely evolved and generalized over the past few years. Now it is commonly used to advocate a generic creation and maintenance of a virtual counterpart (the digital twin) for arbitrary physical object or process (its corresponding physical twin, or PT). Such a DT shall be capable to represent the status, the features, and the behavior of its PT in real time with the possibly finest accuracy.

Such an image inevitably recalls the concept of cyber-physical systems (CPS), which refers to the systems that integrate physical units and processes with software and communication to provide abstractions and techniques for the integrated whole [2]. Actually, any DT system is essentially an indivisible part of a CPS, which enhances the cyber-layer performance with advanced features such as real-time synchronization and high-level information construct [3]. Sometimes, the concept of DT system is also used in a wider sense to denote a subset of CPS, which have DTs implemented on its cyber layer [4]. Regardless the accurate definition, DT is generally believed to revolutionize CPS into its next phase, flourishing and emerging into the latest Fifth Generation (5G) mobile communication systems, not only with an enhancement to all 5G use cases, but also for the conveniences it brings to the test and validation of the 5G network itself [5]. DT is also widely recognized to have a key role to play in the future Sixth Generation (6G) networks, especially in the industrial applications [6]–[9].

Despite the immature conceptualization of 6G, and the debate among different technical proposals, there is one feature of 6G that we know for sure to distinguish it from 5G: the human-centric orientation [8], [10]–[13].

So far till now, the prosperous efforts in DT technologies have been focusing on - as its current definition suggests - bridging the gap between the physical world and the digital world, and have made a great achievement. To pave the way towards a human-centric 6G system, however, we are now challenged by the barriers between the cyber-physical world and the biological world. Reliable and affordable solutions are called for, to enable not only an immersive multi-sense human perception of the virtual world, but also an inclusion of human beings into the objective field of digital twinning.

In this survey, we outline the role of DT in future industrial 6G networking scenarios, identify the challenges induced by human presence and participation in future industry, and the technical requirements of potential solutions to them. We also review the enabling human-machine interface (HMI) technologies, trying to shed the light on possible technical routes to break the human-CPS barriers.

The remainder of this paper is organized as follows: In Sec. II we throw a quick glance at the research trend, the application fields, and the use cases of DT, first in a generic view and then in the context of 6G-empowered future industry. Realizing the essential presence of human in the I4.0 scenario of 6G era, in Sec. III we try to identify the technical challenges introduced by the human-centric DT services, and the technical requirements that must be fulfilled. To overcome these challenges and seamlessly integrate the human participators into the DT-driven industrial practices, in Sec. IV we review the cutting-edge HMI technologies, including human mental status sensing and multi-sensory feedback solutions, attempting to reveal some potential directions for future DT research. To the end, we close the paper with our conclusions in Sec. V.

II. DIGITAL TWIN FOR 6G-EMPOWE TED I4.0

A. Digital Twin: Concepts and Applications

Research interest on the topic of DT has been explosively increasing over the past decade, spreading into various industrial branches, mainly including aviation, healthcare, and manufacturing. As a comprehensive survey [14] shows, the early works were dominantly concentrating on aviation, where the expense of field experiments usually goes beyond affordability, which has encouraged the first burst of research efforts on DT.
Since 2016, however, the focus has overwhelming shifted to the applications of manufacturing and precision medicine.

Despite the common vague opinion that each DT represents its corresponding PT, which we have referred to at the beginning of this paper, an universal agreement on the definition of DT is still in absence. As pointed out by [14]: out of the 75 papers reviewed in that survey, 44 did not give any explicit definition for the concept, while the rest 31 were providing 29 different versions. Taking one more step beyond the analysis by the authors of [14], we can further observe that among the 31 papers that explicitly define DT, 23 are focusing on the field of smart manufacturing, highlighting various key points including integrated system, cyber-cloning, information connections, comprehensive digital construct, simulation test, and virtual replica. Through this superficial mist of a divergence (or even chaos) in opinions about the very same term, we see in DT a wild force driving the modern industry, especially its manufacturing sector, into the new era of future industry.

### B. The 6G Ambition of DT-Driven Industry

Industry 4.0, conceptualized in 2011 [15], seeks to digitalize, automate, and intelligentize the traditional manufacturing and industrial practices with modern smart technologies. Identifying I4.0 as one of its key deployment scenarios, 5G has introduced a gallery of new use cases and technologies for support: the massive machine-type communications (mMTC) to enable dense IoT connections, the ultra reliable low-latency communications (URLLC) to guarantee timely and reliable synchronization, the multi-access edge computing (MEC) to improve accessibility to artificial intelligence, the non-public network architecture to strengthen the security, and the vertical model to deliver heterogeneous services that are tailored to specific industry.

Now, while the deployment of 5G is rapidly spreading over the world, new ambition towards the next generation mobile networks for 2030s have already motivated up-springing research efforts, which aim at pushing everything beyond what 5G promises - and 14.0 cannot be missed. A new concept called Society 5.0 was recently proposed by the government of Japan, which extends the boarder of Industry 4.0 by putting human into the loop of CPS. Coinciding with each other on the human-centric view, Society 5.0 and 6G turn out to be a match made in heaven [16], leading to a pervasive CPS environment with ubiquitous connectivity - not only between everybody, between everything, but also between people and things. This implies to introduce a plethora of emerging human-centric industrial use cases to further enhance I4.0. According to the on-going European 6G flagship project Hexa-X [8], [17], 6G use cases can be clustered into several use case families:

1) **Massive twinning:** where the concept of DT is more fundamentally applied towards a full digital representation, extending the objective of DT to the entire environment, including both the physical and human worlds. This use case family contains not only new DT use cases such as immersive smart city and sustainable food production, but also a deeper integration of DT to the manufacturing environment.

2) **Immersive telepresence for enhanced interactions:** which enables humans to interact with all senses anytime anywhere, either with each other, with physical things, or with digital objects. This use case family opens a door to the future life, where the barrier of physical distance is completely removed for interactions in all fields of human society. The cyber-physical-human worlds will be fully merged by means of mixed reality (MR) and holographic telepresence technologies. In the industrial scenario, multi-sensory tele-interaction and telecollaboration will reshape the current I4.0 vision based on 5G-enabled remote control.

3) **From robots to cobots:** where traditional robotic systems that based on the command-and-control logos will be revolutionized into “cobots” with new symbiotic relations - not only among the cobots each other, but also between the cobots and humans. This will allow cobot systems to perform complex tasks in a collaborative and cognitive fashion. In the consumer electronics market, consumer cobots are expected to better understand and serve the human needs than the off-the-shelf robots today; combined with the emerging AI-as-a-Service promised by 6G, personal AI agents that accompany with humans as autonomous working assistants or even equal partners are appearing no more out of reach. In the industrial environment, the flexible and intelligent collaboration among cobots and humans exhibits to us a bright prospect of flexible manufacturing.

4) **Local trust zones for human and machine:** which aims at protecting privacy by means of dynamically updating the transparency and accessibility of sensitive information that are specific about individuals, machines, or independent networks, w.r.t. use requirements and privacy policies. It further evolves the concept of security trust zone (STZ), which was proposed in 5G regarding cellular topologies [18], [19], to make it apt to the beyond-cellular 6G network topologies, e.g. the “Network of Networks”. It grants trustworthiness to new use cases that are dense of sensitive information and rely on flexible network topology, such as precision healthcare, smart cities, public protection and disaster relief (PPDR), and automatic public security. In the industrial scenario, sensor infrastructure webs and low-power micro-networks will become the key use cases for production and manufacturing.

5) **Sustainable development:** which attempts to address the social concerns about the sustainability of our environment and society, which has been globally growing over the past years, and especially intensified by the extreme weather events and disasters in 2021 (such as the European and Chinese floods, and the heats and wildfires in North America). 6G takes sustainability as one of its key values, and contributes to it with new use cases that emphasize dematerialization, efficient resource usage, and energy-efficient network optimizations, which all count in the industrial scenario.

In summary, we can see in every 6G use case family a significant contribution to further evolve the I4.0. Each of them relies on an accurate, dynamic, real-time, and comprehensive
modeling of all things, humans, and the environment - i.e. the 
upcoming 6G evolution to future industry is deeply rooted in
the deployment of human-centric DT.

III. DT WITH HUMAN PRESENCE IN FUTURE INDUSTRY:
CHALLENGES AND REQUIREMENTS

A. Challenges by Human Existence in Industrial Environment

With the overview above to the future industry based on
6G and DT, we see in it two classes of challenges, namely
the MR-collaboration and the human-disturbance protection,
respectively. Both of them are calling for novel HMI solutions.

On the one hand, the conscious participation of humans in
industrial processes (such as controlling, manufacturing, and
transporting) requires a dependable human-machine collabora-
tion, both in onsite presence and over remote connection.
This implies a huge demand in MR solutions based on multi-
sensory interface. The traditional HMI solutions are dominantly
based on mouse-keyboard-screen (MKS) and audio devices,
shall be extended with haptic feedback, and unperceivable sensing,
so as to allow human users to immersively interact with the cyber world, or interact with
physical objects or other humans in telepresence over the DTs.

On the other hand, the unpredictable human actions,
the presence of humans in industrial environment may usually,
if not always, lead to disturbances or unexpected risky events.
For example, pedestrians wandering in the factory can block
the radio propagation in spectral bands of millimeter wave or
higher frequencies, and therewith cause link failures of the
wireless connected devices. For another instance, a human
participator in industrial process may suffer from abnormal
conditions such as sickness, fatigue, and strong emotions,
which all reduce her level of concentration and comprehen-
sion, and thereby increase the risk of inappropriate operations
that cause failures or dangers. To control and manage these
risks raised by human existence, a timely monitoring of the
health and safety, user’s comfort and convenience
shall be taken into account. This generally requires a compact-
ness of the essential hardware and rejects most (if not all) i n-
vasive interfaces. For example, to recognize facial expressions
and gaits, graphic solutions based on cameras [21], [22] are
preferred in this sense than solutions based on electromyogram
(EMG) signals that can only be measured with electrodes [23],
[24]; should the EMG signals be measured, surface electrodes
are much preferred than needle electrodes.

3) Dependability: for applications intolerant to outages, 6G
intends to deliver guarantees for multiple end-to-end (E2E)
performances, such as achievable data rate, maximum E2E
core latency, bounded jitter, and E2E packet reliability with
robust mobility. This is known as the concept of dependabil-
ity [8], which is especially critical for use cases such as human-
machine interaction and automation. As an essential stage of
the E2E service chain in 6G-driven industrial DT, the HMI
must cope with these requirements.

4) Electromagnetic Compatibility: massive twinning in in-
dustrial scenario inevitably leads to a complex electromagnetic
environment, where strong interference and noise may proba-
ably occur, sometimes even randomly and without predictable
pattern. The HMI solution therefore must be electromagneti-
cally robust to ensure its reliability. On the other hand, it shall
not generate strong electromagnetic leakages that interfere
with the wireless channels or other devices.

5) Sustainability: 6G takes sustainability also as one of
its key values. This does not only mean that 6G shall foster
improved sustainability in various societal domains, but also
implies that 6G itself must be made sustainable. Unsustainable
technologies, which depend on nonrenewable resources, use
pollutive materials, or generate high CO2 emission, shall not be adopted in 6G - with no exception for the HMI.

6) Security and privacy: As 6G will, with its ubiquitous
coverage and massive twinning, connect all things and people
with each other, and carry massive data that describe them
comprehensively and in detail like never before, it also raises
concerns in security and privacy to an unprecedented level.
On the one hand, enhanced security measures must be taken
to guard the user data unauthorized accesses and malicious
operations by an non-trusted person or third party. On the other
hand, the user data also need to be protected from possible
inappropriate exploitation by the trusted ones, such like the
industrial verticals. For instance, the General Data Protection
Regulation (GDPR) of European Union prohibits a handful
kinds of data processing that can leak the user identity or
lead to discrimination, with only a few exceptions under very strict rules. How to exploit human-specific data in DT systems (especially those with DTs of humans), while staying aligned with such regulations, must be taken into consideration when designing the HMI.

IV. HMIS FOR HUMAN-CENTRIC DT: AN OVERVIEW

Like we have discussed above, technical challenges for future industrial DT systems with human presence are identified in both aspects of HMI: the sensorlogic one of sensing and monitoring of human status from the machine side, as well as the perceptual one of generating feedback in MR environment to humans. On the sensorlogic side, mature solutions to sense and monitor the mobility and physical status (e.g. body temperature, pulse rate, etc.) have been well developed and widely applied in commercial personal devices over the past decade, while the sensing of mental status is remaining as an open issue. On the perceptual side, conventional technologies are still generally relying on visual and auditory senses, leaving the other human senses (tactile, olfactory, and gustatory) barely exploited. To inspire innovations towards an immersive human-centric industrial DT, we give here an overview to the potential technical enablers of human mental status sensing and multi-sensory feedback.

A. Sensing the Mental Status

Industrial processes can be greatly impacted by the mental status of the human participants, not only regarding the quality of output/product, but more importantly, regarding the safety of system and humans themselves. The most critical mental signals to be measured include:

1) Comprehension: in industrial scenarios, especially regarding human-machine collaboration, it is usually important for the intelligent systems to confirm that the human has perceived and understood the critical information it provides, such like a notification, an inquiry, an instruction, or a warning.

2) Concentration: distraction from the task in processing in industrial environment can easily lead to operation failures, which may cause serious losses and dangers.

3) Fatigue: fatigue generally reduces the level of concentration. Besides, it also weakens human’s strength, agility, precision, and endurance in physical tasks; and degrades the human cognitive abilities in all aspects. In addition, continuous working under fatigue is likely to damage the health.

4) Emotion: negative emotions such as depression, stress, anxiety and anger can regularly lead to distraction, and accelerates the increase of fatigue. With the significant impact on the human behavior pattern, extreme emotions may also cause failures of human-related prediction algorithms.

Since direct sensing of the mental status is impossible, people have developed a handful of indirect approaches to estimate it from measurable physical features. Such physical features that are typically taken as indicators include:

1) Speech voice: emotions and fatigue can significantly change the tone, speed, volume and timbre of one’s speech voice. Hence, they can be detected through vocal analysis. However, to continuously monitor the mental status of a person in this way, the person has to keep talking, which is not universally possible. Nevertheless, in some certain scenarios where the vocal signal is available, e.g. when vocal commands are used to control the intelligent system, voice-based mental status estimation can be well integrated.

2) Facial expressions: rich information about one’s mental status can be mined from her facial expressions and microexpressions, which has been exploited by human beings for thousands of centuries as most classical and reliable approach of emotion recognition. This approach requires images or videos that capture most facial areas - in sufficiently high resolution and ideally in the front view - of the person under analysis, which are easy to obtain in most industrial scenarios.

3) Galvanic skin response signal: shifting in the intensity of emotional states can cause effects in human’s eccrine sweat gland activity, which change the conductance of skin. Such effects are almost immediate to the emotional arousal, and easy to measure with wearable devices.

4) Eye movements: eye movement have been used since long as a psychological signal for emotion recognition. It can be captured either from video by cameras and eye trackers, or from electrooculogram signals by specialized electrodes. Both can be easily integrated into wearable devices such like VR/AR headsets.

5) Bioelectric signals: there are a variety of bioelectric signals widely used in psychological and clinical studies to identify human brain activities and mental status, common examples include electroencephalogram (EEG), electromyogram (EMG), electrooculogram (EOG), and electrocardiogram (ECG). They usually need to be sensed with specialized electrodes, which are not always convenient and comfort to carry while working in the industrial environment.

Some examples of mental status sensing are listed in Tab. I.

| Mental signal | Physical feature | Literature |
|---------------|-----------------|------------|
| Comprehension | Facial expression | [25] |
|               | Galvanic skin response | [26] |
|               | Eye movements | [27] |
|               | Bioelectric signals | [28] |
| Concentration | Facial expression | [29], [30] |
|               | Bioelectric signals | [31] |
| Fatigue       | Speech voice | [32] |
|               | Facial expression | [33] |
|               | Galvanic skin response | [34] |
|               | Eye movements | [35] |
|               | Bioelectric signals | [36] |
| Emotion       | Speech voice | [37] |
|               | Facial expression | [38] |
|               | Galvanic skin response | [39], [40] |
|               | Eye movements | [41] |
|               | Bioelectric signals | [42] |
B. Multi-Sensory Feedback

Since vision is most important sense of human, visual user interface (UI) will still indefinitely remain the dominating approach for machines sending information to humans. However, the traditional visual UI based on text and two-dimensional graphics cannot fulfill the requirements of future industrial DT applications such like MR, immersive telepresence and human-robot collaboration, and therefore must be extended.

1) Holographic vision: As the successor of text, image, video and 3D video, holography will be the fifth generation of visual user interface technology. Allowing such a visualization of DT, that no clear boundary is to be sensed between the virtual objects and the real physical environment, holographic vision plays a key role in the future DT applications including MR, immersive telepresence, and telecollaboration.

There have been already commercial holographic vision products released, which have also been applied in research works, such as the Microsoft HoloLens 2 [43]. They have been proven sufficient as solutions to optically deliver MR. To achieve the target of teleinteraction and telecollaboration, however, there are still two main challenges to overcome. First, the closed-loop latency must be minimized, taking into account the computing delay to update the holographic model of DT regarding human actions (e.g. pressing a button on the holographic projection of a machine), so as to realize a smooth teleinteraction experience. Second, when multiple users are involved with, e.g. in telecollaboration, the holographic image/video must be highly synchronized for all users. Both challenges are related to the research areas of URLLC, information freshness, and time-sensitive networking (TSN).

2) Tactile: Alongside with vision, the mostly used human sense, there is the tactile that is used by us in every physical contact of ours with the environment or any object. Being partly processed by the spinal cord instead of the brain, tactile is also the most agile sense of humans, responding significantly faster than the visual and auditory senses [44]. Since the concept of Tactile Internet being proposed in 2014 [45], the telecommunication community has been struggling to achieve the target of $\leq 10\text{ms}$ E2E latency, which is the limit of tactile cognition for humans. In the wireless field, the 5G URLLC use case was proposed to address this issue, breeding numerous research works over the past years.

Despite the significant progress in evolving the network infrastructure to support tactile internet, haptic solutions to generate agile and accurate tactile feedback are still far behind the requirements of future industry. The haptic interface is a critical enabler for industrial DT applications, not only because it enriches the user experience of sensing virtual objects with tactile, but also as a necessary condition of reliable motion-capture-based remote operation. Only with an accurate and fast haptic stimulus that vividly simulates the weight, resistance and hardness of physical objects, it becomes possible for a human user to appropriately exert and accomplish high-precision tasks such like surgery over teleinteraction.

Traditional solutions to provide tactile feedback are mostly extrinsic, i.e. they rely on instrumented environment with active devices, such like vibrators-embedded steering wheels for virtual automotive driving [46], and the vibration-based tactile simulation of physical keyboard on [47]. Such solutions are generally limited to local area and specific use scenarios. To enable tactile feedback in immersive and ubiquitous teleinteraction with arbitrary object, the intrinsic solutions try to augment the user instead of the environment, and alter the user’s tactile perception. This can be typically realized by wearable haptic devices, or through direct stimulation to the user’s neurosensory mechanism [48]. Recently, there has been a new class of methods developed, which use drones to flexibly generate tactile feedbacks [49], [50].

3) Other senses: In addition, other senses such as smell and taste may also be useful in some industrial scenarios, but the physicalization of them is remaining a technical challenge [51].

V. Conclusion

In this paper we have provided our vision on the role played by DT in future 6G-empowered industry. We have identified the gaps, technical requirements and challenges for novel HMI solutions in such industrial DT applications, taking a human-centric point of view. We have also surveyed the main potential technology routes and candidate solutions, hoping to inspire interested peers towards the next breakthrough in this field.

REFERENCES

[1] Michael Grieves, “Digital twin: manufacturing excellence through virtual factory replication,” white paper, March 2014.
[2] J. Shi, J. Wan, H. Yan, and H. Suo, “A survey of cyber-physical systems,” in 2011 International Conference on Wireless Communications and Signal Processing (WCSP), 2011, pp. 1–6.
[3] K. Josifovska, E. Yigitbas, and G. Engels, “Reference framework for digital twins within cyber-physical systems,” in 2019 IEEE/ACM 5th International Workshop on Software Engineering for Smart Cyber-Physical Systems (SEsCPS), 2019, pp. 25–31.
[4] C. Kan and C. J. Anumba, “Digital twins as the next phase of cyber-physical systems in construction,” in Computing in Civil Engineering 2019: Data, Sensing, and Analytics, Reston, VA: American Society of Civil Engineers, 2019, pp. 256–264.
[5] H. X. Nguyen, R. Resttian, D. To, and M. Tatipamula, “Digital twin for 5G and beyond,” in IEEE Communications Magazine, vol. 59, no. 2, pp. 10–15, February 2021.
[6] Y. Wu, K. Zhang, and Y. Zhang, “Digital Twin Networks: A Survey,” in IEEE Internet of Things Journal, vol. 8, no. 18, pp. 13789–13804, September 2021.
[7] H. Viswanathan and P. E. Mogensen, “Communications in the 6G Era,” in IEEE Access, vol. 8, pp. 57063–57074, 2020.
[8] M. A. Uustalato et al., “Hexa-X The European 6G flagship project,” in 2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), 2021, pp. 580–585.
[9] AI@EDGE, “D2.1: Use cases, requirements, and preliminary system architecture,” June 2021. https://aitedge.eu/wp-content/uploads/2021/09/AI@EDGE_D2.1_Use-cases-requirements-and-preliminary-system-architecture.-pdf
[10] S. Dang, O. Anfin, B. Shuhada, et al., “What should 6G be?”, in Nature Electronics, vol. 3, pp. 20—29, 2020.
[11] W. Saad, M. Bennis, and M. Chen, “A Vision of 6G wireless systems: Applications, trends, technologies, and open research problems,” in IEEE Network, vol. 34, no. 3, pp. 134–142, May/June 2020.
[12] Z. Zhang et al., “6G wireless networks: Vision, requirements, architecture, and key technologies,” in IEEE Vehicular Technology Magazine, vol. 14, no. 3, pp. 28–41, September 2019.
[13] L. U. Khan, I. Yagooob, M. Imam, Z. Han, and C. S. Hong, “6G wireless systems: A vision, architectural elements, and future directions,” in IEEE Access, vol. 8, pp. 147029–147044, 2020.
