Frontiers of Transdisciplinary Research in Tactile Internet with Human-in-the-Loop

Frank H.P. Fitzek*†, Shu-Chen Li‡†, Stefanie Speidel§†, Thorsten Strufe¶†, and Patrick Seeling‖
*Deutsche Telekom Chair of Communication Networks - Technische Universität Dresden, Germany
Email: frank.fitzek@tu-dresden.de
†Centre for Tactile Internet with Human-in-Loop (CeTI)
‡Chair of Lifespan Developmental Neuroscience - Technische Universität Dresden, Germany
Email: shu-chen.li@tu-dresden.de
§Division of Translational Surgical Oncology - National Center for Tumor Diseases, Partner Site Dresden, Germany
Email: stefanie.speidel@nct-dresden.de
¶KASTEL Security Research Labs - Karlsruhe Institute of Technology, Karlsruhe, Germany
Email: thorsten.strufe@tu-dresden.de
‖Department of Computer Science - Central Michigan University, Mount Pleasant, MI, USA
Email: patrick.seeling@cmich.edu

IGARSS 2021 - 2021 IEEE International Geoscience and Remote Sensing Symposium | 978-1-6654-0369-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/ISWCS49558.2021.9562223

Abstract—**Recent technological advances in developing intelligent telecommunication networks, ultra-compact bendable wireless transceiver chips, adaptive wearable sensors and actuators, and secure computing infrastructures along with the progress made in psychology and neuroscience for understanding neurocognitive and computational principles of human behavior combined have paved the way for a new field of research: Tactile Internet with Human-in-the-Loop (TaHiL). This emerging field of transdisciplinary research aims to promote next generation digitalized human-machine interactions in perceived real time. To achieve this goal, mechanisms and principles of human goal-directed multisensory perception and action need to be integrated into technological designs for breakthrough innovations in mobile telecommunication, electronics and materials engineering, as well as computing. This overview highlights key challenges and the frontiers of research in the new field of TaHiL. Revolutionizing the current Internet as a digital infrastructure for sharing visual and auditory information globally, the TaHiL research will enable humans to share tactile and haptic information and thus veridically immerse themselves into virtual, remote, or inaccessible real environments to exchange skills and expertise with other humans or machines for applications in medicine, industry, and the Internet of Skills.**

Index Terms—**Tactile Internet, Human-in-the-Loop, Internet of Skills, Cyber-physical systems, Human-machine adaptation, Intelligent networks, Multisensory perception, Goal-directed behavior**

I. Introduction

The Internet's story is one of continuous evolution, typically driven by a combination of technological enablers, their market availability, and a non-abating human need for information, entertainment, and social connectedness. This transformation has propelled the Internet from its data-driven initial application over the democratized access and distribution of information to the rich immersive media streaming and social network Internet of today. The broad availability of increasingly affordable hardware and more and more user friendly means of becoming connected, including via portable smart devices, has provided a democratized access to the Internet and its services (such as the World Wide Web) wherever data connectivity is available, i.e., independent of space and time.

At this inflection point in time, the Internet and several industries are undergoing another radical transformation. This transformation places the human actor at its center, with the current Internet providing the starting point for the significant changes required. The next generation of the Internet, the Tactile Internet (TI), has been defined by the Institute of Electrical and Electronics Engineers (IEEE) P1918.1 Tactile Internet Standardization Working Group as: "A network or network of networks for remotely accessing, perceiving, manipulating or controlling real, or virtual objects, or processes in perceived real-time by humans or machines" [1], [2]. This new concept moves from the notion of information to one of sensing and actuating, with human and machine operators seamlessly connected.

This places the Human-in-the-Loop (HITL) at the center of control loops [3] that have human senses and their machine representations as command and feedback content for sensing and actuating. This digitized exchange of human cognition, action, and perception will require new underlying mechanisms, such as dynamically allocated ultra-low latency and high throughput computing resources, that are the promise of the TI. The integration of both as the Tactile Internet with Human-in-the-Loop (TaHiL) will enable a democratized access to skills and expertise. While HITL systems have been around for some time, their adoptions have been hampered by a lack of networked integration and an holistic approach that focuses on the human element, which is at the core of TaHiL research. This new focus has the ability of a revolution in access to skills and expertise with full equity, i.e., independent of age, gender, cultural background, abilities, as well as space and time.

Intuitively, the realization of the breakthrough TaHiL concept will require a multitude of research domains to join at this nexus. In turn, transdisciplinary research is needed that combines psychology, cognitive neuroscience, medicine, computer science, as well as electrical, mechanical, and material engineering domains. In the following, we initially provide an overview of requirements deriving from the multisensory human perception before we describe the transfer of skills in the TaHiL concept and research approaches that incorporate the outlined concepts.

II. Senses and Skills

Placing human operators into control loops inherently requires these operators to perceive the environment through

978-1-7281-7432-7/21/$31.00 ©2021 IEEE

their senses, process the information, and perform actions based on the processing outcomes. As equitable access is required, even this initial description already hints at required considerations for people of different ability levels and age groups. Broadly enabling human operators to be immersed in virtual, remote, or inaccessible real environments to collaboratively work with machines and other humans will require a consideration of the individual human senses, as well as their development over time. Similar considerations can be applied to the development of skills and expertise.

A Cyber-Physical System (CPS) that enables bi-directional information processing in real-time closed-loop interactions between humans and machines connected over networks needs to be designed and evaluated with respect to its impact on the digitization on human goal-directed multisensory perception and action. Current research mainly focuses on each of the human senses individually, with latency requirements from around 10 ms for video over about 3 ms for audio to only 1 ms for haptic [4], [5]. While humans can compensate for increased latencies [6], the challenge to reduce the latency and provide multimodal feedback remains.

Solving this challenge will require transdisciplinary research for engineering designs, hardware, software, and real-time approaches based on psychophysiological and even neurocognitive principles incorporating a broad variety of human factors. The HITL component in TaHiL environments requires the appropriate regard of these factors as they influence not only the efficiency of developed future solutions, but also the well-being of the human operators in-the-loop. This subsequently requires new and grounded models that are applicable for heterogeneous populations to ensure equitable access. Furthermore, human-machine interactions require co-adaptation models that can dynamically adjust for factors such as age and experience and their influence in multi-sensory human operator experiences. This also drives the requirements for the underlying TaHiL systems to potentially have tightened latency requirements or a need for different perceptual coding as part of the digitization process.

The goal-directed multisensory processing also requires multimodal feedback that allows for the design of new immersive human-machine interfaces. The multimodal feedback optimized for different human operator multisensory processing complicates the development of general-purpose sensing and actuating models and devices as different psychophysical parameters apply for the different senses and users. The principle of just-noticeable differences is one example that highlights how to derive thresholds for sensing/actuation and signal compression for a specific sense. The interplay of individually compressed senses in a multisensory interface, however, has not been extensively researched for broad human populations and factors. For example, research at the Centre for Tactile Internet with Human-in-Loop (CeTI) demonstrated that perceptual quality assessment of vibrotactile signals based on human psychophysical data is helpful for selecting between tactile codecs [7]. Latency-optimized sensors and actuators are as essential as the TI that connects them with latency-optimized computational resources, but currently existing solutions are not latency-optimized and not geared towards the requirements of the TI.

A. Transferring Skills: Human → Machine

A human operator requires a user interface that ideally facilitates the local or remote control of a machine. Generally, through the user interface, the HITL controls a machine to transfer a skill, typically based on specific movement commands and received feedback. This represents a stark contrast to prior generations of typically (pre-)programmed machine routines. A variability between control modalities due to different interfaces and different underlying machine particularities can render this task increasingly complex and difficult to adapt to. Furthermore, user interfaces that are not intuitive and difficult to use can increase the operator's cognitive strain through increased complexity, negatively impacting the Quality of Interaction (QoI).

Wearable devices have the potential to become part of a new user interface for the TaHiL. Their operation via tracking of human motion and mapping the sensed information to current and anticipated behavior and robot actions can commonly be performed by information technology novices, providing equity through removal of entrance barriers. In turn, any domain expert becomes enabled to initialize the skill transfer from human to machine. A hurdle for this type of interface in the context of TaHiL is the correctly synchronized multimodal feedback, with latency limiting the physical distance between the operator and machine, as also noted in Section!III. Each individual sense in the multimodal feedback needs to also be considered individually as well as in interplay. For example, haptic information is typically small in data size, but requires ultra-low latency (ULL), while video is typically higher in bandwidth, but tolerates delay. Both need to be satisfied and ideally synchronized so that any human operator can be fully immersed, which again is a significant challenge requiring a transdisciplinary approach.

B. Transferring Skills: Human ← Machine

Provided with multimodal feedback components of next-generation user interfaces, machines become enabled to transfer skills to human operators. The combination of sensors and actuators can be employed in the wearables constituting part of these user interfaces and effectively control the HITL. For example, specific gestures or motion paths can be generated in real-time or offline and the human operator be notified when deviating from the planned path. Contraptions as simple as smart functional tapes, made of smart fabrics with sensors and vibro-tactile feedback are under investigation in attempts to improve skill performance and learning [8]. Additionally, this provides a great opportunity for scenarios of repetition and training, for example in physical rehabilitation and training, where a remote physiotherapist could generate a pre-recorded movement exercise as treatment that is transmitted to a cyber-physical system at the patient's home. The patient can then perform repetitive exercises and be monitored and automatically corrected when deviating from the prescribed exercise regime. The gathered data from the patient side can subsequently be used to determine progress and refine the training.

C. The Internet of Skills: Human ↔ Machine

With the digital transfer of skills between humans and machines, humans will be able to immerse themselves into a

Fig. 1. Example highlighting the TaHiL enabled Internet of Skills: Human skills are digitized and transported over intelligent networks, before being applied via actuators, robots, or other means. The tactile information control loop in the Tactile Internet limits the real-time loop latency to 1 ms.

mix of real, virtual, local, remote, past, and present environments to collaboratively work with machines and exchange skills with machines as well as other humans, termed the Internet of Skills [8], [9]. The digitized skills in the TaHiL context enable direct skill transfers between different human or machine participants, as illustrated in Figure 1. Once digitized skills become networked, they can be stored and dynamically re-applied in new scenarios. In this scenario, a synchronous skill transfer could be completed via digitization of actions, subsequent delivery with the help of the TI, and guidance a the remote HITL. Digitally mediated learning could even store the characteristics defining a specific skill, which then could be delivered asynchronously to learners. Such approach removes time and place from the skill transfer between humans and enables the permanent archiving of skills as technological cultural resources for future generations. This democratization of skills and expertise across distance, time, and socio-economical boundaries can have significant impacts on humanity's future.

D. Examples

In the following, we highlight two examples for Industry 5.0 [10] and robot-assisted surgery application scenarios for the Internet of Skills.

1) Internet of Skills for Industry 5.0: Moving past the machine-to-machine communications, cyber-physical systems [11], and data centricity of Industry 4.0 [12], Industry 5.0 will be disrupted by TaHiL applications [13]. While on one hand industrial processes become standardized and reap productivity increases through real-time systems with the help of robots, production also increasingly shifts to smaller, more customized product batches. Both can benefit from the TI [14], [15], but the one-off intelligent robot-assisted production will greatly benefit from the ability to intuitively control and program fully automatized production environments through advancements in computing as well as human-machine collaboration and adaptation [9].

For example, a programming-centric approach for controlling machines in industrial settings requires a domain expert to communicate with a programming expert to develop the detailed machine instructions, which are fixed after several iterations and testing. This process incurs significant overhead in time and cost to derive a networked synchronization of a specific production line that is statically (for the production run) defined by the involved steps. In turn, the thus developed solution is typically not transferable to different production environments (such as machine type differences) without additional overhead. Even more resources would be required for a modification or a complete new production line, such as in one-off or small batch productions. Employing an intuitive user interface that records direct human-to-robot instructions, after several repetitions by the human expert, machine learning can be employed to automatically generate the program for the individual robot. Following the TaHiL approach we described throughout, this teaching can be performed at a distance, even further reducing the need for a local expert and enabling a new economy of remote experts providing production instructions.

2) Internet of Skills for Surgery: While robot-assisted surgery has made great inroads in recent years, not all potentials are currently realized – this limits the benefits of systems employed to date. Significant improvements in patient care and outcomes could be realized if TaHiL methods and technologies [16] could be employed, such as for enabling remote surgery applications [17]. In addition, context-aware human-machine collaboration could provide real-time assistance similar to an experienced human assistant [18]. Such support will require the system to understand situations and enable skill transfers, experts demonstrating operations are needed in sensor-outfitted environments [19], [20]. (We note that while the idea of skill acquisition, learning, and transfer here is similar to the industrial scenario, the overall complexity is significantly higher due to the extensive increased number of environmental factors in a highly dynamic scenario.) Gathered annotated data from various sources enable based on machine-learning approaches to model surgical skills [17], [21] and allow semi-automation of surgical skills like knot-tying, suturing, laparoscope guidance or sonography tasks [22]–[25].

For direct control in HITL scenarios at a distance, the TI provides the latency-optimized communication components. Novel machine-learning approaches are needed that are designed around continuous perception, analysis, prediction, and reasoning in a latency-constrained framework. Not only do these systems need to provide current situational awareness, but also incorporate the entire surgical workflow [26], [27]. The realization of the TaHiL promise will democratize surgical skills by quantifying surgical experience and make it accessible to machines.

III. Transdisciplinary Research Frontiers

Several overarching research themes emerge from the outlined potentials and challenges for the realization of the TaHiL. The strong HITL focus requires new models for human goal-directed behavior, which can enable predictions of actions based on sensation, multisensory perception, cognition, and actions. To support the multimodal feedback in the loop, new wearable devices for ultra-low latency sensing and actuating are required, which need to be small, bendable, stretchable, and ultra-low-power. Their input/output data has to be networked employing ultra-low latency and reliable communications. 0.1 ms for the wireless and wired transmission and reception For the tactile dimension example in a generic TaHiL control loop, the 1 ms round-trip delay allocation [28] yields: 0.1 ms for the embedded sensing processing,

processing, 0.125 ms budget for propagation delay over a distance up to 25 km, 0.35 ms for the computing processing at the edge computing site, 0.125 ms for propagation, 0.1 ms for the wireless and wired transmission and reception processing, and 0.1 ms for the embedded actuator processing. The previous steps require significant consideration of human factors in novel coding and compression methods for sensing and actuating (e.g., haptic codecs or compressed sensing) as well as for networked data transport (e.g., network coding). The data generated from multimodal feedback and for multisensory experiences needs to be placed into continuously evolving frameworks of mutually adaptive learning between humans and machines for skill acquisition and training. This requires a secure and scalable computing infrastructure that is highly adaptive to changes in task contexts and world models. As none of these challenges are solvable within a single discipline, the realization of the TaHiL vision necessitates a transdisciplinary research approach.

A. Human Perception and Action

The creation of new digital environments that become enabled through the TaHiL capabilities will require a host of new technologies in the cyber-physical realm. One of the primary domains of interest stems from the human-machine interface's need for multisensory processing, likely resulting in new hardware and software solutions. In turn, these solutions need to be optimized for the ultra-low latency requirements in the outlined closed-loop human-machine interaction scenarios. This requires a deeper understanding for human goal-directed multisensory perception and action to derive suitable models. Following the goals of the TaHiL, these need to consider individual human operator differences, such as age and expertise levels, to ensure equitable access to the future Internet of Skills.

Skill acquisition and mastery, human development [29], and aging [30], [31] can significant impact the efficiency of developed engineering designs if not considered explicitly. Human factors need to be explicitly considered, and requires research beyond the current state of understanding, especially expertise- and age-related differences in key parameters of multisensory integration and delay requirements. This will require psychophysical and and neurocognitive experimentation with large numbers of human subjects to derive equitable ground truth models for individual sensory modalities (e.g., auditory, visual, and haptic) as well as their interplays in broad scenarios. The intricate interplays of goals, perceptual interdependencies, and sensorimotor tasks need to be modeled not only for individuals, but also considering and predicting expertise- and age-related differences [32].

B. Human-Machine Co-augmentation

With multimodal feedback driving the next generation of human-machine interfaces for TaHiL applications, new fast and flexible sensors and actuators are needed. For example, eGloves and eBodySuits could combine sensing and multimodal outputs for human multisensory processing. Throughout the closed-loop of sensing, networking, processing, and actuating, the human psychophysical characteristics define the requirements for sensing, compression, and actuators forming the multimodal interfaces. Specific psychophysical considerations, such as the just noticeable level of difference [33], in turn provide the limits for specific senses and the processing needs for immersive feedback. The tactile and kinesthetic components commonly are the most latency sensitive, and codecs need to be developed that combine efficient compression with ultra-low latency and resilience. Furthermore, synchronization between different multisensory data streams will need to be investigated and new approaches are required beyond current ones.

Flanking the more software-centric development of adaptive codecs, new types electronics will need to be developed. They have to support real-time operation while consuming very low energy using only a very small footprint. Only this combination will enable the human and CPS to be equipped with a large number of sensors and actuators to support a natural interface design. As human operators will likely employ wearable designs, the electronic hardware has to be bendable and stretchable as well as wirelessly connected for a significant amount of time (energy efficiency) in real-time scenarios. This limits the dimensions for transceivers to ideally be on-chip (attainable with very high communication frequencies) and requires the design of highly optimized power consumption approaches in real-time operation modes that aggressively cycle with only nanoseconds of delay between deep sleep and operating modes. Several computing components will be prohibitive on-chip for sensors and actuators, but would incur too much networking overhead when considering local edge clouds [34]. For these, local preprocessing and computing is required on-body to guarantee low latency, and new high-performance body computing platforms are needed.

C. Human-Machine Networks

Significant development strides are needed in communications networks from body area over local area to wide area networks that augment the network operations beyond only relaying of information. The tight latency requirements for some multisensory components in TaHiL scenarios, as well as opposing high bandwidth needs for others, require dynamically adjustable networks. Softwarization, including software-defined networks, network function virtualization, and information-centric networking, are already making inroads into deployed networks, but need to be exploited with respect to low latency and learning capabilities [28]. With network learning capabilities, the multimodal information (i.e., audio, video, and haptic) can be used in on-the-fly network capability adaptation (e.g., network slicing). Furthermore, intelligence within the network is required to enable new functionalities that TaHiL scenarios require due to their nature: in case of interruptions, the network should locally (and transparently) compensate, e.g., through the prediction of the goal-driven human actions in a mobile edge cloud. This type of approach is only possible through a deeper understanding of the abstract high-level mental models as well as the low-level sensorimotor programs of human operators. Furthermore, they need to exploit additional knowledge that is needed on the human ability to cope with delays, ambiguities, and disruptions. A deeper understanding of these underlying human concepts is not only needed for the design and implementation of communication networks, but also prerequisite for the design of human–technology feedback strategies on all levels. Ultimately, solving this challenge has the ability to solve the competition between latency, bandwidth, and resilience, with tremendously implications beyond TaHiL applications.

D. Human-Machine Communication

Current control systems are predominantly employing wired physical connections due to the robustness offered and challenges in wireless systems when finding optimum operational parameters for the trade-off between latency, resilience, and throughput. The human–machine cohabitation underlying the TaHiL approach will produce massive amounts of control loop information. In contrast to prior control loop communications, however, the data exchange for TaHiL applications needs to employ wireless communications to enable freedom of movement for humans and machines. New compression approaches, such as those for haptic information [35] are needed to reduce the sensor and actuator data. While some similarities to source compression for audio and video exist, the latency limitations imposed on these new codecs require special considerations in contrast to prior approaches. Similarly, the increased amount of data also necessitates compression to be evaluated in form of distributed approaches, where network coding and compressed sensing can be employed to provide a reduction of data to be transmitted over networks. The in-network computing additionally allows for further data reduction by exploiting the closed-loop human–machine interactions through machine learning. Each newly developed approach also needs to be tailored to the software-defined networks and network virtualization solutions that will be part of TI networks. As a final research challenge, one has to consider that each of these developments cannot be regarded individually, but has to consider the impacts on the HITL. This, similar to the Quality of Experience in multimedia compression developments, requires a significant amount of human subject experimentation to determine a user's Quality of Interaction. As human subject experimentation is not feasible on a very large scale, objective quality metrics will be required that reliably and equitably map to subjective HITL experiences.

E. Human-Machine Learning

As highlighted throughout, artificial intelligence and specifically machine learning approaches will be of significant importance for the realization of the TaHiL's potential. While humans will be augmented by machines, machines will need to become enabled to learn on different time scales of human behavior. This needs to encompass not only the transfer of expertise and its continued development, but also the utilization of the systems by human operators themselves. To enable truly immersive human-machine integration, a system's end-users need to become aware of the rationale behind the decisions that are taken by machines so as to anticipate them and integrate them. The predictability of actions from humans and machines will thus enable each side to support the other and usher in a time of fully immersed human–machine cooperation and co-augmentation. This evolution of human-machine cooperation requires new models, methods, and tools that combine the multisensory experience with goals and multimodal feedback intricacies we described throughout. Solutions need to incorporate non-linear dynamic models for human decision-making that are grounded in neuroscientific advances. Additionally, explanations for machine behaviors, machine-learning results, and other components of the multimodal interactions need to be developed that can be presented to humans in different stages of skill development. A significant challenge here lies in the development of equitable approaches that are applicable for a large number of situational factors.

F. Human–Machine Computing

The realization of the TaHiL is synonymous with an increase of softwarization from sensors/actuators over the network edge to its core, and the connecting network components. The multisensory experience that a HITL will experience in the services built on top of the TI requires not only fast, but also resilient underlying architectures and resources. This encompasses not only failures or privacy concerns, but also the potential for attacks on TaHiL applications and services. For example, the increasingly immersive nature of TaHiL scenarios results in more directly human-attached sensor readings, which could uniquely identify individuals [36]. Not only does this circumvent privacy, but can be further exploited to gather sensitive information about the HITL [37]. The aggregation and training of models does not exclude these approaches [38]. Resiliency to attacks [39], [40] needs to be designed under the strict latency requirements of the TI. New approaches combining safety, security, privacy, and scalability in ultra-low latency settings are needed to provide the decentralized tactile computing infrastructure (computation, networking, storage) in the classical CIA domains of confidentiality [41], integrity [42], and availability [43]. As TaHiL systems span the range from low-resourced sensors to high-resourced cloud-based components, the upcoming frameworks need to be adaptable for a broad range of components. Furthermore, they need to be able to be adapted over time, as system components, protocols, and applications for the TaHil continuously evolve and provide new services across industries.

IV. Conclusion

The Tactile Internet with Human-in-the-Loop (TaHiL) combines human factors, ultra-low latency requirements across all computing resources as well as on sensor and actuator combinations, and a resulting need for transdisciplinary research and development. TaHiL applications in industry, medicine, and, more generally, the Internet of Skills have tremendous potential for the future. The full realization of this potential requires new approaches across a broad range of transdisciplinary fields, such as new developments of codecs that drive digitization in new domains, intelligent networks that enable resilient ultra-low latency, augmented perception that takes human factors into account, or co-adaptation that enables collaborative life-long learning between humans and machines. The combinations of these approaches go significantly further than prior approaches simply focusing on Human-in-the-Loop control systems or for providing cross-media context-sensitive information. The result of these efforts will be a revolution in the future of work, life, and leisure activities.

Acknowledgments

Funded by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany's Excellence Strategy – EXC 2050/1 – Project ID 390696704 – Cluster of Excellence "Centre for Tactile Internet with

Human-in-the-Loop" (CeTI) of Technische Universität Dresden.

REFERENCES

[1] G. P. Fettweis, "The Tactile Internet: Applications and challenges," *IEEE Vehicular Technology Magazine*, vol. 9, no. 1, pp. 64–70, Mar. 2014.

[2] D. Szabo, A. Gulyás, F. H. P. Fitzek, and D. E. Lucani Rötter, "Towards the Tactile Internet: Decreasing communication latency with network coding and software defined networking," in *Proceedings of the European Wireless Conference (EW)*, May 2015, pp. 1–6.

[3] G. Schirner, D. Erdogmus, K. Chowdhury, and T. Padir, "The future of Human-in-the-Loop cyber-physical systems," *Computer*, vol. 46, no. 1, pp. 36–45, 2013.

[4] Y. Yang and A. M. Zador, "Differences in sensitivity to neural timing among cortical areas," *Journal of Neuroscience*, vol. 32, no. 43, pp. 15 142–15 147, 2012.

[5] A. Dix, J. R. Helmert, and S. Pannasch, "Latency in cyber-physical systems: the role of visual feedback delays on manual skill learning," in *Proceedings of the 5th International Conference on Human Interaction and Emerging Technologies (IHIET 2021)*, 2021, accepted for publication.

[6] Y. Chen, T. Farley, and N. Ye, "Qos requirements of network applications on the internet," *Inf. Knowl. Syst. Manag.*, vol. 4, no. 1, p. 55–76, Jan. 2004.

[7] E. Muschter, A. Noll, J. Zhao, R. Hassen, M. Strese, B. Guelecyuez, S.-C. Li, and E. Steinbach, "Perceptual quality assessment of compressed vibrotactile signals through comparative judgment," *IEEE Transactions on Haptics*, pp. 1–1, 2021.

[8] L. Oppici, T. Bobbe, L.-M. Lüneburg, A. Nocke, A. Schwendicke, H. Winger, J. Krzywinski, C. Cherif, T. Strufe, and S. Narciss, *Internet of Skills*. Academic Press, 2021, ch. 4, pp. 77–102.

[9] M. Dohler, T. Mahmoodi, M. A. Lema, M. Condoluci, F. Sardis, K. Antonakoglou, and H. Aghvami, "Internet of skills, where robotics meets AI, 5G and the Tactile Internet," in *Proceedings of the European Conference on Networks and Communications (EuCNC)*, 2017.

[10] S. Nahavandi, "Industry 5.0—a human-centric solution," *Sustainability*, vol. 11, no. 16, 2019. [Online]. Available: https://www.mdpi.com/2071-1050/11/16/4371

[11] N. Jazdi, "Cyber physical systems in the context of industry 4.0," in *2014 IEEE International Conference on Automation, Quality and Testing, Robotics*, 2014, pp. 1–4.

[12] M. Wollschlaeger, T. Sauter, and J. Jasperneite, "The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0," *IEEE Industrial Electronics Magazine*, vol. 11, no. 1, pp. 17–27, 2017.

[13] A. Aijaz and M. Sooriyabandara, "The tactile internet for industries: A review," *Proceedings of the IEEE*, vol. 107, no. 2, pp. 414–435, 2018.

[14] Y. Bai, "Industrial Internet of things over tactile Internet in the context of intelligent manufacturing," *Cluster Computing*, vol. 21, no. 1, pp. 869–877, 2018.

[15] S. Haddadin, L. Johannsmeier, and F. D. Ledezma, "Tactile robots as a central embodiment of the tactile Internet," *Proceedings of the IEEE*, vol. 107, no. 2, pp. 471–487, 2018.

[16] F. H. Fitzek, S.-C. Li, S. Speidel, T. Strufe, M. Simsek, and M. Reisslein, Eds., *Tactile Internet with Human-in-the-Loop*, 1st ed. New York: Academic Press, 2021.

[17] L. Maier-Hein, S. S. Vedula, S. Speidel, N. Navab, R. Kikinis, A. Park, M. Eisenmann, H. Feussner, G. Forestier, S. Giannarou, M. Hashizume, D. Katic, H. Kenngott, M. Kranzfelder, A. Malpani, K. März, T. Neumuth, N. Padoy, C. Pugh, N. Schoch, D. Stoyanov, R. Taylor, M. Wagner, G. D. Hager, and P. Jannin, "Surgical data science for next-generation interventions," *Nature Biomedical Engineering*, vol. 1, no. 9, pp. 691–696, 2017.

[18] D. Katić, A.-L. Wekerle, J. Görtler, P. Spengler, S. Bodenstedt, S. Röhl, S. Suwelack, H. G. Kenngott, M. Wagner, B. P. Müller-Stich *et al.*, "Context-aware augmented reality in laparoscopic surgery," *Computerized Medical Imaging and Graphics*, vol. 37, no. 2, pp. 174–182, 2013.

[19] S. S. Vedula, M. Ishii, and G. D. Hager, "Objective assessment of surgical technical skill and competency in the operating room," *Annual Review of Biomedical Engineering*, vol. 19, pp. 301–325, 2017.

[20] T. Vercauteren, M. Unberath, N. Padoy, and N. Navab, "CAI4CAI: the rise of contextual artificial intelligence in computer-assisted interventions," *Proceedings of the IEEE*, vol. 108, no. 1, pp. 198–214, 2019.

[21] S. Bodenstedt, D. Rivoir, A. Jenke, M. Wagner, M. Breucha, B. Müller-Stich, S. T. Mees, J. Weitz, and S. Speidel, "Active learning using deep Bayesian networks for surgical workflow analysis," *International Journal of Computer Assisted Radiology and Surgery*, vol. 14, no. 6, pp. 1079–1087, 2019.

[22] A. Shademan, R. S. Decker, J. D. Opfermann, S. Leonard, A. Krieger, and P. C. Kim, "Supervised autonomous robotic soft tissue surgery," *Science Translational Medicine*, vol. 8, no. 337, pp. 337ra64.1–337ra64.8, 2016.

[23] E. De Momi, L. Kranendonk, M. Valenti, N. Enayati, and G. Ferrigno, "A neural network-based approach for trajectory planning in robot–human handover tasks," *Frontiers in Robotics and AI*, vol. 3, pp. 34.1–34.10, 2016.

[24] H. Mayer, F. Gomez, D. Wierstra, I. Nagy, A. Knoll, and J. Schmidhuber, "A system for robotic heart surgery that learns to tie knots using recurrent neural networks," *Advanced Robotics*, vol. 22, no. 13-14, pp. 1521–1537, 2008.

[25] M. Antico, F. Sasazawa, L. Wu, A. Jaiprakash, J. Roberts, R. Crawford, A. K. Pandey, and D. Fontanarosa, "Ultrasound guidance in minimally invasive robotic procedures," *Medical Image Analysis*, vol. 54, pp. 149–167, 2019.

[26] D. Rivoir, S. Bodenstedt, I. Funke, F. von Bechtolsheim, M. Distler, J. Weitz, and S. Speidel, "Rethinking anticipation tasks: Uncertainty-aware anticipation of sparse surgical instrument usage for context-aware assistance," in *Proc. Int. Conf. on Medical Image Computing and Computer-Assisted Intervention*. Springer, 2020, pp. 752–762.

[27] S. Bodenstedt, M. Wagner, L. Mündermann, H. Kenngott, B. Müller-Stich, M. Breucha, S. T. Mees, J. Weitz, and S. Speidel, "Prediction of laparoscopic procedure duration using unlabeled, multimodal sensor data," *International Journal of Computer Assisted Radiology and Surgery*, vol. 14, no. 6, pp. 1089–1095, 2019.

[28] Z. Xiang, F. Gabriel, E. Urbano, G. T. Nguyen, M. Reisslein, and F. H. Fitzek, "Reducing latency in virtual machines: Enabling tactile Internet for human-machine co-working," *IEEE Journal on Selected Areas in Communications*, vol. 37, no. 5, pp. 1098–1116, 2019.

[29] A. Bremner, D. Lewkowicz, and C. Spence, *Multisensory Development*. Oxford University Press, 2012.

[30] S.-C. Li, U. Lindenberger, B. Hommel, G. Aschersleben, W. Prinz, and P. Baltes, "Transformations in the couplings among intellectual abilities and constituent cognitive processes across the life span," *Psychological Science*, vol. 15, no. 3, pp. 155–163, 2004.

[31] S.-C. Li and A. Rieckmann, "Neuromodulation and aging: implications of aging neuronal gain control on cognition," *Current Opinion in Neurobiology*, vol. 29, pp. 148–158, 2004.

[32] S.-C. Li, E. Muschter, J. Limanowski, and A. Hatzipanayioti, *Human perception and neurocognitive development across the lifespan*. Academic Press, 2021, ch. 9, pp. 199–221.

[33] E. Weber, *Die Lehre vom Tastsinn und Gemeingefuehl, auf Versuche gegruendet. London, UK.: Verlag Friedrich Vieweg und Sohn, Braunschweig: translated (1978) The sense of touch*. Academic Press, 1978.

[34] J. A. Cabrera, R.-S. Schmoll, G. T. Nguyen, S. Pandi, and F. H. Fitzek, "Softwarization and network coding in the mobile edge cloud for the tactile internet," *Proc. of the IEEE*, vol. 107, no. 2, pp. 350–363, 2018.

[35] E. Steinbach, S. Hirche, J. Kammerl, I. Vittorias, and R. Chaudhari, "Haptic data compression and communication," *IEEE Signal Processing Magazine*, vol. 28, no. 1, pp. 87–96, 2010.

[36] C. Deußer, S. Passmann, and T. Strufe, "Browsing unicity: On the limits of anonymizing web tracking data," in *Proceedings of the IEEE Symposium on Security and Privacy (S&P)*, 2020.

[37] M. Kosinski, D. Stillwell, and T. Graepel, "Private traits and attributes are predictable from digital records of human behavior," *Proceedings of the National Academy of Sciences*, vol. 110, no. 15, pp. 5802–5805, 2013. [Online]. Available: https://www.pnas.org/content/110/15/5802

[38] D. Wunderlich, D. Bernau, F. Aldà, J. Parra-Arnau, and T. Strufe, "On the privacy-utility trade-off in differentially private hierarchical text classification," *CoRR*, vol. abs/2103.02895, 2021.

[39] A. Osman, A. Wasicek, S. Köpsell, and T. Strufe, "Transparent microsegmentation in smart home iot networks," in *Proc. of the USENIX Workshop on Hot Topics in Edge Computing*, 2020.

[40] A. Osman, P. Brückner, H. Salah, F. H. P. Fitzek, T. Strufe, and M. Fischer, "Sandnet: Towards high quality of deception in container-based microservice architectures," in *Proceedings of the IEEE International Conference on Communications (ICC)*, 2019.

[41] J. A. C. Guerrero, F. H. P. Fitzek, S. Hanisch, S. A. W. Itting, J. Zhang, S. Zimmermann, T. Strufe, M. Simsek, and C. W. Fetzer, *Intelligent networks*. Academic Press, 2021, ch. 6, pp. 135–154.

[42] F. Armknecht, P. Walther, G. Tsudik, M. Beck, and T. Strufe, "Promacs: Progressive and resynchronizing macs for continuous efficient authentication of message streams," in *Proceedings of the ACM SIGSAC Conference on Computer and Communications Security*, ser. CCS. New York, NY, USA: Association for Computing Machinery, 2020, p. 211–223. [Online]. Available: https://doi.org/10.1145/3372297.3423349

[43] U. Aßmann, C. Baier, C. Dubslaff, D. Grzelak, S. Hanisch, A. P. P. Hartono, S. Köpsell, T. Lin, and T. Strufe, *Tactile computing: Essential building blocks for the Tactile Internet*. Academic Press, 2021, ch. 13, pp. 293–317.