Feedback Presentation for Workers in Industrial Environments – Challenges and Opportunities

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Abstract. On the long term, the current wave of digitization and automation in the industrial environment will result in a progressively higher complexity and heterogeneity in the industrial environment. In this context, a growing need arises for the development of digital assistance systems to support workers in various fields of activities. Current systems are generally limited to visualizations and visual feedback. Therefore, in the scope of this paper, we take a look at the major challenges and opportunities for the integration of multimodal feedback systems in today's and future industrial environments. It shows that the integration of multimodal feedback is subject to a complex combination of technical, user-centric and legal aspects.

Keywords: Human-Machine-Interaction · Multimodal Feedback · Assistive Systems · Augmented-Reality · Smart Factory

1 Introduction

Today's industrial landscape is characterized by a mixture of analogue and digital production facilities. As a result of the advancing digitization and automation in the industrial sector, this situation will change significantly in the upcoming years and the number of intelligent production facilities, so-called smart factories, will steadily increase. These smart environments will be characterized by complex digital and automated production systems, robots, autonomous transport vehicles, sensor systems and a high number of other digital devices [1, 2]. At the same time, these changes will also shift the role of the worker in the industrial environment and most of the workers will primarily be employed in the field of monitoring, maintenance and logistics rather than in the area of assembly [25, 8]. The activities in the field of assembly, on the other hand, will in future be limited to specific tasks that cannot be automated due to the emerging high product diversity and short production cycles. In order to facilitate the completion of these activities and to ensure the safety of people in these dynamic, highly automated areas, extensive and individually customizable assistance systems will be required. These systems in form of digital equipped workplaces or various mobile devices will have to provide workers with relevant information about their surroundings or ongoing and upcoming tasks. At the same time, these systems must also inform their users about

relevant situations within their environment as well as possible dangers such as autonomous vehicles or robots around their workplaces. For this reason, an integration of adequate feedback methods will be necessary for the implementation of future assistance systems which aim to extend and enrich the interaction between a user and a digital system by providing information over different sensory channels [5].
But, despite the opportunities to improve the support for workers, an extensive integration of feedback systems also raises numerous challenges regarding technical, user-related and legal aspects. Thus, adequate feedback presentations require a deep integration of the related systems into the infrastructure of a production facility to get access to relevant information about ongoing processes and production systems. In addition, these systems will have to meet certain requirements regarding their usability and user experience, as well as data security and privacy regulations in the workplace.
Therefore, as part of this paper, we want to introduce and discuss key challenges and opportunities for the integration of multimodal feedback systems for industrial applications. In the second part we will first look at the current state of research in the field of feedback technologies and adaptive assistance systems. Then, in part three and four, we will discuss the major challenges and opportunities for the application of multimodal feedback systems in the industrial environment. Finally, in part five and six, we will discuss our findings and provide an outlook towards future research activities in this context.

2 Related Work

2.1 Feedback Modalities and Feedback Devices

Feedback represents an essential component of human learning and behavior. Generally, according to the *principle of actio et reactio*, it can be seen as the reaction of an environment to an action performed by an individual within it [6]. The positive or negative evaluation of this reaction has an impact on subsequent actions and can influence future behavior in similar situations. Feedback is percepted through a variety of different sensations via the various sensory channels of the human body such as seeing, hearing, feeling, smelling, tasting as well as kinesthetics [5]. These modalities are used to create an internal representation of the environment and to build or expand knowledge about the interaction between different entities and actions. Feedback is thereby provided via a single sensory channel or through a combination of different channels, often referred to as multimodal feedback [7]. Multimodal actuations are generally offering a more natural and trusted perception as long as the provided sensations are corresponding to plausible procedures [8, 9]. But various studies also revealed that a combination of a primary and a supporting feedback dimension is often more effective than a combination of three or more feedback dimensions [8, 9, 10, 11, 12].

Regarding digital devices, visual feedback is carried out via different forms of light sources, stationary and mobile displays, digital projections and head-mounted displays (HMDs). The provided information ranges from simple status lights or color changes over symbols to images, text and animations. Auditory feedback, on the other hand, is presented over speakers or headphones and ranges from simple acoustic signals over signal patterns to spoken language. Haptic feedback, in this sense, is divided into tactile feedback and kinesthetic feedback. Tactile feedback addresses the human sense of touch and is usually presented through vibrations, while kinesthetic perception refers to the posture and movement of the joints as well as the perception of external forces that are performed against the body [7]. Especially the development of haptic and tactile systems has increased considerably in recent years [13, 14]. Currently, an important aspect concerns the integration of tactile actuators into various garments, such as work gloves [15, 16], bracelets [17, 18] or shoes [19, 20] to provide workers with additional tactile information.

2.2 Assistive Systems for Industrial Applications

In recent years, the increasing digitization and automation has triggered a trend towards the development of assistive systems to support workers on various activities in the industrial environment. These assistance systems provide their users with step-by-step instructions for daily tasks but may also display further information such as machine-related or process-related data as well as warnings about faulty actions or potential dangers in the environment. The application of these systems ranges from assembly tasks over maintenance operations to activities in the field of logistics. The devices used for this purpose include normal PCs or mobile devices such as smartphones and tablet PCs. But, due to the ongoing developments in the field of augmented reality (AR) as well as in the field of mobile devices and wearables, current assistance systems progressively focus on the implementation of augmented reality scenarios. These systems use in-situ projections, special AR tablet PCs or AR HMDs to project digital information directly into the field of view of a user. Figure **1** shows an overview of different visualization technologies for todays and future assistive systems.

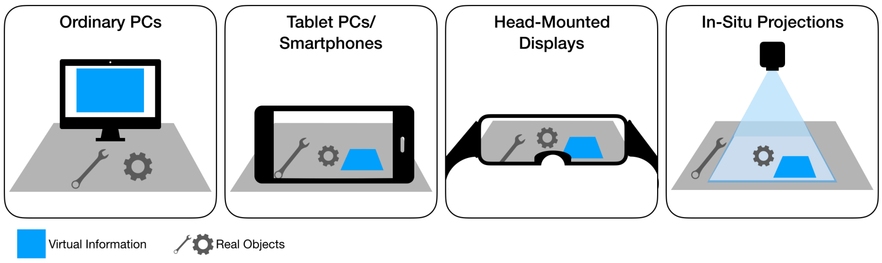

Fig. 1. Overview of visualization technologies for todays and future assistive systems.

Stationary assistive systems for assembly tasks like the assembly tables presented by Funk et al. [21] and Büttner et al. [22] use a combination of in-situ projections and a recognition of hand movements via deep cameras. Thus, the system allows to project information directly into the working area. The interaction with the system is implemented via hand-tracking based on the integrated depth camera, e.g. via virtual buttons. Assistive systems for maintenance tasks such as the systems presented by Zheng et al. [23] and Aromaa et al. [24], on the other hand, are usually based on AR tablet-PCs, AR HMDs and wearables in order to allow the implementation of mobile maintenance scenarios.

However, regarding the provision of feedback, stationary and mobile assistive systems for industrial applications are generally restricted to a presentation of information via the visual channel. The extension of these systems by additional feedback modalities is still ongoing research: Funk et al. [8] and Kosch et al. [12], for example, prototypically extended an assembly workplace with devices for the presentation of auditory and tactile error feedback in order to evaluate the effectiveness and user experience of the different modalities.

3 Challenges for Feedback Presentation in Industrial Environments

Various interdisciplinary challenges arise for the integration and application of multimodal feedback systems in the industrial environment. This includes both technical and user related as well as legal aspects and addresses different research fields such as human-machine interaction, industrial communication, machine learning, artificial intelligence, sensor technologies, workplace privacy and data security.

3.1 Integration of Feedback Systems in the Industrial Infrastructure

From a technological point of view, a major challenge concerns the general integration of feedback systems in industrial environments. To provide workers with adequate feedback, these systems must be able to collect and process information about the environment. In this context, today's industrial facilities are already equipped with certain kinds of sensory systems to collect information about air pressure, power consumption, the localization of materials, vehicles and employees or other parameters. In future industrial facilities, however, the number of sensory systems needs to increase significantly in order to create decent virtual representations of the environment including ongoing processes, power management, material flows, errors, and other relevant information. Due to the high dynamics and complexity of future production plants, various sensors as well as powerful algorithms for scene analysis and processing are required in order to develop context-aware processes and workflows [25]. Figure **2** shows an abstract overview for the integration of feedback systems in industrial environments. Feedback devices as part of assistance systems for various activities are both connected via the digital system of the respective workplace as well as via the central server system. This enables feedback to be applied in relation to local and production-wide processes.

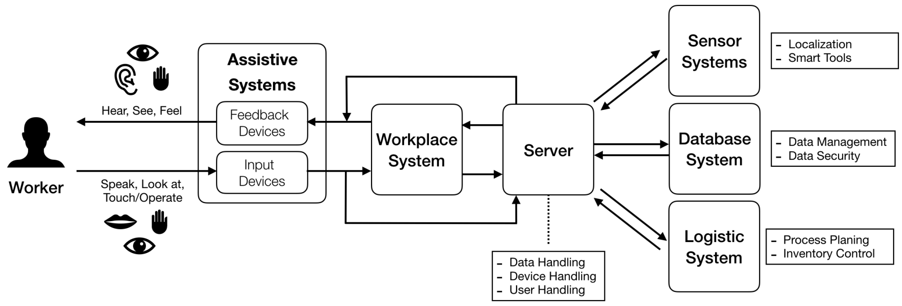

Fig. 2. Overview of the general integration for feedback devices in an industrial environment

Developments in the field of industrial communication technology are currently splitting into various research tracks which follow the implementation of industrial network infrastructures using different technologies. The solutions range from local server systems to cloud-based systems and various intermediate solutions which hold relevant data locally and, if necessary, retrieve additional data from a cloud service [26, 27]. The implementation of the communication channels, however, is currently frequently carried out via a combination of wired and radio-based networks to connect the growing number of stationary and mobile digital systems in today's industrial environments. But due to the progressive development of mobile systems in the research area of the Internet of Things, which aims to digitalize and interconnect various systems in order to generate a virtual representation of ongoing processes and connections, there is a growing need for a wireless network solution for industrial environments that provides the required high bandwidth and low latency [28, 29, 30]. In this context, the 5g technology, also known as the Tactile Internet, which is based on mobile communication technologies, aims to integrate industrial plants and other digital devices in industrial environments into a nationwide internet ready network [26, 31].

3.2 Data Processing

Because of the complexity of industrial networks, the collection, processing and analysis of the high number of heterogeneous data streams, generated by numerous sensors, production systems and other entities requires efficient algorithms and concepts [32]. In this field, scientists are increasingly relying on the use of developments in the field of machine learning and artificial intelligence in order to be able to identify different relationships and situations [33, 34]. This contextual sensitivity, in turn, makes it possible to draw conclusions about the correct or incorrect execution of actions by individual workers to initiate an adequate response.

Regarding the presentation of multimodal feedback, humans are sensory impressions are subject to certain temporal limits during which time a reaction is perceived as natural. This also represents a strong temporal limitation for the processing and presentation of relevant feedback information. For the auditory system, this limit is about 100 ms, while the visual system is limited to 10 ms and the haptic system to 1 ms [35, 36]. While the performance of auditory and visual feedback information is already achieved via today's network structures, the realization of the transmission of haptic information is still a current research subject, which is currently challenged by researchers in the scope of the development of 5G technologies, also referred to as Tactile or Haptic Internet [31, 36]. In general, it must be ensured that the processing and transmission of feedback information corresponds to the temporal limits of human information processing.

3.3 External Influences

Another key challenge for the integration of feedback systems in the industrial environment concerns external influences that could affect both workers and sensory systems [37, 38]. This primarily includes changing volume and light conditions as well as various forms of vibrations caused by machines or tools. These influences are very likely to have a negative impact on the performance of feedback. For example, a purely visual feedback could be disturbed by light influences such as apertures or particularly bright ambient lights. The performance of auditory feedback such as alert tones or spoken text could also be disturbed by a high ambient volume. Furthermore, tactile feedback could be overlaid by vibrations generated by production systems or work tools. External influences, however, may not only affect the provision of feedback directly, but could also influence sensory systems in the surrounding which in turn are highly relevant for the presentation of feedback. The application of feedback systems therefore requires a detailed analysis of the working environment and the tools needed to carry out the respective activity.

3.4 User Acceptance

A further user-related challenge concerns the acceptance of workers towards modern technologies, especially with regard to interaction and feedback devices. While younger generations are generally more familiar with the functionality and application of modern interaction and feedback systems, there are some high dislikes on the part of older generations regarding these kind of systems [39, 40]. Röcker [41] identified different societal and technological as well as privacy-related concerns towards the usage of new technologies in future work environments. Furthermore, Holzinger et al. [42] introduced a "previous exposure to technology" factor which has general influence on the acceptance of software applications. Another influence on the acceptance of digital systems stems from the increasing use of methods from machine learning and artificial intelligence (AI). Since these methods have to be regarded as black boxes, it is nearly impossible to understand their internal behavior. This raises the general question if we can trust results from machine learning [43] and how we can build explainable AI systems [44].

3.5 Data Security and Workplace Privacy

Another challenge directly related with user acceptance concerns the implementation of directives on data protection and workplace privacy in industrial environments. This especially includes personal data from employees as well as data collected by assistive systems, interaction and feedback devices. These systems are able to capture complex information about the performance and location of workers and are therefore often viewed as a potential way to monitor employees which would negatively affect their workplace privacy [45, 46, 47]. The same also applies to the previously described sensory systems for the localization of different entities in an industrial environment [48, 49]. However, personal data is required in this context in order to ensure the adaptiveness of the assistance systems and thus also the individual adaptation of the presentation of feedback information. According to Sack and Röcker [50] knowledge about technical processes is influenced by age and technology experience while the knowledge over technical processes is not related with attitudes like security or privacy. Thus, the confidence in technology and the reduction of privacy concerns has to be build up by the designers and developers of future assistive systems and feedback devices [51].

3.6 Selection of Feedback Devices and Feedback Presentations

A further challenge which is highly related to user acceptance and workplace privacy arises through the selection of suitable feedback systems for the application in industrial environments. These systems can generally be categorized in portable and stationary devices. While portable systems are able to provide a location-independent presentation of feedback modalities, they open up a greater potential for long-term monitoring in terms of acceptance and workplace privacy (Section **3.4**). In contrast, stationary feedback systems integrated in the working environment are limited to certain areas and may therefore provide a lower sense of permanent monitoring. But, compared to mobile systems, stationary systems are not able to provide feedback to users outside their workspace. Furthermore, a common use of stationary feedback systems by several people also has to be considered as critical, because provided information is likely to be misinterpreted by another user.

Another aspect concerns the potential overlay or attenuation of sensory sensations caused by feedback systems. For example, data gloves can provide a much more detailed feedback in the execution of manual activities. But overlaying the skin with one or more layers of fabric may lead to a lowering of the sensation of the haptic receptors. Moreover, the construction of some portable systems can lead to a restriction of freedom of movement.

In addition to the selection of applicable feedback systems, the choice of an adequate presentation of feedback information is also of high importance. In this context, Funk et al. [52] evaluated different visualization techniques to support an assembly task for impaired workers. In general, due to the growing number of devices in the area of interaction technologies, it will be necessary to develop new technology-specific concepts for the presentation of feedback over visual, acoustic and tactile channels. Furthermore, the acceptance towards a system is also dependent on its proper functionality. With regard to feedback systems, the focus here is primarily on fulfilling the temporal limitation of the human information processing of various information channels described in Section **3.2**.

3.7 Cognitive Workload

Another user-related challenge concerns the increasing cognitive load generated by a huge amount of digital information passed to workers in modern industrial environments [53, 54]. To reduce the cognitive load of workers, intelligent filter routines are necessary, which analyze the existing data streams based on different parameters such as the experience level, the current activity, the position and the surroundings of a worker in order to select individual relevant information. In this context, a broad examination towards the individual perception of cognitive stress will be necessary. Thereby, particularly HMDs are known to cause headaches and dizziness during prolonged use [55, 56]. Potential reasons for this are likely to be found in the limited ergonomics of these systems and the extensive presentation of additional visual information which leads to a constant change of the visual focus between digital information and the real world. Furthermore, it is important to evaluate how a long-term presentation of multimodal feedback sensations through digital Feedback devices affects the cognitive workload.

4 Opportunities for Feedback Presentation in Industrial Environments

Despite the challenges and problems presented in Section **3**, the integration of multimodal feedback technologies opens up numerous opportunities to assist workers by carrying out their activities and to improve the overall productivity and security. Furthermore, these systems can also be used to extend and enrich interaction concepts of augmented-reality technologies or to support even workers with certain cognitive or motoric disabilities, blindness or deafness on daily tasks.

4.1 Assistive Systems

In the first place, the use of effective multimodal feedback methods in future industrial environments offers the possibility to extend existing assistance systems, which aim to adequately support workers by providing step-by-step instructions and further information about upcoming tasks and activities as well as warnings about errors or critical situations. In addition, the comprehensive integration of these systems into the digital infrastructure of industrial production environments can provide a more comprehensive feedback that exceeds the limits of the immediate environment of the workplace.

As described in Section **2**, current assistance systems are usually limited to visual feedback presentations to assist workers. This in turn may contribute to a reduced usability and user experience. The presentation of feedback over multiple channels could thereby create a more natural and trusted loop of interaction between the system and the worker. In this context, the evaluations of various feedback modalities for the support of an assembly operation presented by Funk et al [8] and Kosch et al [12] are just to be seen as the beginning of an extensive evaluation process to identify adequate feedback devices and presentations for different activities in the industrial environment.

During the last years, developments in the field of assistive systems are increasingly relying on AR technologies. But recently developed devices such as AR tablet-PCs, AR

HMDs or in-situ projectors still suffer from limited multimodal feedback implementations. Thereby, a presentation of multimodal feedback information in an AR scenario could create a much more natural and trustful relation between virtual and real objects [9]. In this way, for example, gesture-based interaction could be enhanced with tactile or auditory impressions. However, the use of such systems, in particular in the form of HMDs, will also require an extensive evaluation of the respective activity, the environment as well as the behavior and the cognitive burden of the user in order to create an adequate feedback presentation.

4.2 Inclusion of People with Disabilities

In addition to increasing the productivity and safety of healthy workers in different fields of activity, the use of multimodal feedback systems as part of assistive systems also offers the opportunity to especially support people with certain disabilities on different activities. During the years, several assistive technologies have been developed and evaluated to assist people with motoric or cognitive disabilities as well as blindness or deafness in private life as well as at the workplace [57]. Regarding the industrial environment, developments of assistive technologies for people with disabilities mainly focus on assembly operations supported via in-situ projections and motion tracking [58]. In this context, Korn [59] evaluated the application of gamification elements during an assembly task to support cognitively impaired people on an assembly task. Furthermore, Kosch et al. [12] further compared visual, auditory and tactile feedback methods to support impaired workers at an assembly task and Funk et al. [52] also evaluated different visualization techniques to support an assembly task for impaired workers. The results of these studies show that people with different disabilities can benefit from the provision of additional feedback information to perform operations that are normally too complex with respect to their performance index. In general, assistive systems can represent a long-term opportunity for a greater autonomy and an increased self-esteem for people with disabilities, and also a possibility for full-fledged occupational participation in the first labour market [57].

But especially the development of systems for people with disabilities requires a comprehensive evaluation of technological, social and legal aspects. Therefore, regarding impaired workers, feedback systems should fulfill specific guidelines and regulations like the German Federal Ordinance on Barrier-Free Information Technology [60] which holds detailed information about how to implement visualizations and other feedback modalities in a barrier-free way.

5 Conclusion

In this paper, we examined major challenges and opportunities for the presentation of multimodal feedback in todays and future industrial environments. We have shown that the emerging challenges are of a highly interdisciplinary nature, addressing fields like human-machine interaction, industrial communication, machine learning, artificial intelligence, sensor technologies, workplace privacy, data security and occupational science (Section **3**). But the key challenges such as the choice of feedback devices and feedback presentations, the technology acceptance of workers or the privacy at the workplace can primarily be seen as highly user-related.

As mentioned in Section **1**, in the upcoming years the role of workers in the industrial environment will shift from assembly activities to controlling and logistical tasks as well as maintenance operations. Since these tasks mainly represent mobile activities, mobile assistance systems and feedback systems will be increasingly needed to support workers in changing environments and at different production facilities. This, in turn, requires a distinct way to capture changing working environments in mobile scenarios. However, prior to the development of these assistive systems, it is essential to carry out a detailed analysis of the environment and the respective activity as well as of the devices involved in order to be able to perform a selection of the appropriate feedback modalities and devices. As discussed in Section **4.2,** an additional aspect also emerges through the development of systems for people with disabilities. In this context, additional analyses for the determination of individual needs will be required to provide adequate support for workers with different disabilities.

Technical aspects, on the other hand, are focused on the integration of feedback technologies into the digital infrastructure of today's and future industrial environments. Current research thereby offers several solutions for an extensive integration of feedback systems (Section **3.1**). While the 5G technology offers an interconnection between a high number of digital devices in a nationwide network, also a basic combination of wired and wireless networks with the required low latency and high bandwidth would be possible.

In addition to the various challenges, the possibilities for the integration of feedback systems presented in Section **4** prove to be highly relevant. The development and extension of assistance systems through various feedback modalities can contribute to higher productivity and higher safety of workers in future industrial environments. Especially, in the context of augmented reality devices as well as for the support of workers with certain disabilities, multimodal feedback could be highly beneficial.

Taking into account the potentially prevailing environmental influences in industrial environments such as changing lights and noise as well as vibrations generated by machines or work tools, effective combinations of different feedback modalities for certain working environments and fields of activity are required (Section **3.3**). But, since the user-centered provision of auditory feedback in certain areas would only be feasible with headphones or target-oriented loudspeakers, which could potentially cause excessive attenuation of ambient noise or a limitation of privacy [8], developers may prefer combinations of visual and tactile feedback systems. In some cases, however, it may be necessary to further supplement the used portable feedback systems by using stationary interface-specific feedback systems in order to improve the overall usability and user experience.

In general, especially due to the rapid development of new interaction systems, we see high needs for research activities regarding the selection of appropriate feedback systems and the associated presentation methods to extend assistive systems for industrial environments.

6 Outlook

Regarding the integration of multimodal feedback systems, our future research will primarily be focused on questions concerning the selection of suitable devices and presentation techniques for the support of stationary and mobile activities in different occupational fields in industrial environments. This also includes the evaluation of various commercial and in-house development systems within the framework of comprehensive user studies and surveys on the effectiveness, acceptance and usability of various device combinations. Due to the changing role of workers in the industrial environment, our research will be oriented towards the development of systems for mobile scenarios based on augmented reality technologies. In close cooperation with research colleagues from the fields of industrial communication technology, machine learning and artificial intelligence as well as the field of occupational sciences, we want to discuss necessary aspects of the requirements regarding the network infrastructure, the data processing and the usability and user experience for integrating feedback systems into industrial environments in order to examine potential solutions.

7 Acknowledgments

This work is funded by the German Federal Ministry of Education and Research (BMBF) for project ADIMA under grant number 13FH019PX5.

References

1. Fellmann, M., Robert, S., Büttner, S., Mucha, H., & Röcker, C. (2017). Towards a Framework for Assistance Systems to Support Work Processes in Smart Factories. In: A. Holzinger P. Kieseberg, A M. Tjoa, E. Weippl (Eds.): *Machine Learning and Knowledge Extraction.* Springer, Heidelberg, Germany, pp. 59 - 68.
2. Radziwon, A., Bilberg, A., Bogers, M., & Madsen, E. S. (2014). The smart factory: exploring adaptive and flexible manufacturing solutions. *Procedia Engineering*, *69*, 1184-1190.
3. Brettel, M., Friederichsen, N., Keller, M., & Rosenberg, M. (2014). How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 Perspective. *International Journal of Mechanical, Industrial Science and Engineering*, *8*(1), 37-44.
4. Gorecky, D., Schmitt, M., Loskyll, M., & Zühlke, D. (2014, July). Human-machine-interaction in the industry 4.0 era. In *Industrial Informatics (INDIN), 2014 12th IEEE International Conference on* (pp. 289-294). IEEE.
5. Salvendy, G. (2012). *Handbook of human factors and ergonomics*. John Wiley & Sons.
6. Aström, K. J., & Murray, R. M. (2010). *Feedback systems: an introduction for scientists and engineers*. Princeton university press.
7. Rodrigues, J., Cardoso, P., Monteiro, J., & Figueiredo, M. (Eds.). (2016). *Handbook of Research on Human-computer Interfaces, Developments, and Applications*. IGI Global.
8. Funk, M., Heusler, J., Akcay, E., Weiland, K., & Schmidt, A. (2016, June). Haptic, Auditory, or Visual?: Towards Optimal Error Feedback at Manual Assembly Workplaces. In *Proceedings of the 9th ACM International Conference on PErvasive Technologies Related to Assistive Environments* (p. 43). ACM.

9. Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. *Psychonomic bulletin & review*, *20*(1), 21-53.
10. Vitense, H. S., Jacko, J. A., & Emery, V. K. (2003). Multimodal feedback: an assessment of performance and mental workload. *Ergonomics*, *46*(1-3), 68-87.
11. Hecht, D., & Reiner, M. (2009). Sensory dominance in combinations of audio, visual and haptic stimuli. *Experimental brain research*, *193*(2), 307-314.
12. Kosch, T., Kettner, R., Funk, M., & Schmidt, A. (2016, October). Comparing tactile, auditory, and visual assembly error-feedback for workers with cognitive impairments. In *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility* (pp. 53-60). ACM.
13. Benali-Khoudja, M., Hafez, M., Alexandre, J. M., & Kheddar, A. (2004, March). Tactile interfaces: a state-of-the-art survey. In *Int. Symposium on Robotics* (Vol. 31, pp. 23-26).
14. Stone, R. J. (2001). Haptic feedback: A brief history from telepresence to virtual reality. In *Haptic Human-Computer Interaction* (pp. 1-16). Springer, Berlin, Heidelberg.
15. Hsieh, Y. T., Jylhä, A., & Jacucci, G. (2014, October). Pointing and selecting with tactile glove in 3D environment. In *International Workshop on Symbiotic Interaction* (pp. 133-137). Springer, Cham.
16. Moy, G., Wagner, C., & Fearing, R. S. (2000). A compliant tactile display for teletaction. In *Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on* (Vol. 4, pp. 3409-3415). IEEE.
17. Matscheko, M., Ferscha, A., Riener, A., & Lehner, M. (2010, October). Tactor placement in wrist worn wearables. In *Wearable Computers (ISWC), 2010 International Symposium on* (pp. 1-8). IEEE.
18. Brock, A., Kammoun, S., Macé, M., & Jouffrais, C. (2014). Using wrist vibrations to guide hand movement and whole body navigation. *i-com*, *13*(3), 19-28.
19. Fu, X., & Li, D. (2005, January). Haptic shoes: representing information by vibration. In *proceedings of the 2005 Asia-Pacific symposium on Information visualisation-Volume 45* (pp. 47-50). Australian Computer Society, Inc.
20. Xu, Q., Gan, T., Chia, S. C., Li, L., Lim, J. H., & Kyaw, P. K. (2016, December). Design and Evaluation of Vibrating Footwear for Navigation Assistance to Visually Impaired People. In *Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData), 2016 IEEE International Conference on* (pp. 305-310). IEEE.
21. Funk, M., Korn, O., & Schmidt, A. (2014). Assisitive augmentation at the manual assembly workplace using in-situ projection. In *Proceeding of the chi workshop on assistive augmentation* (p. 11).
22. Büttner, S., Sand, O., & Röcker, C. (2015, August). Extending the design space in industrial manufacturing through mobile projection. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct* (pp. 1130-1133). ACM.
23. Zheng, X. S., Foucault, C., Matos da Silva, P., Dasari, S., Yang, T., & Goose, S. (2015, April). Eye-wearable technology for machine maintenance: Effects of display position and hands-free operation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 2125-2134). ACM.
24. Aromaa, S., Aaltonen, I., Kaasinen, E., Elo, J., & Parkkinen, I. (2016, October). Use of wearable and augmented reality technologies in industrial maintenance work. In *Proceedings of the 20th international academic mindtrek conference* (pp. 235-242). ACM.

25. Wieland, M., Kopp, O., Nicklas, D., & Leymann, F. (2007, June). Towards context-aware workflows. In *CAiSE07 Proc. of the Workshops and Doctoral Consortium* (Vol. 2, No. S 25, p. 78).
26. Wollschlaeger, M., Sauter, T., & Jasperneite, J. (2017). The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0. *IEEE Industrial Electronics Magazine*, *11*(1), 17-27.
27. Ehrlich, M., Wisniewski, L., & Jasperneite, J. (2018). State of the art and future applications of industrial wireless sensor networks. In *Kommunikation und Bildverarbeitung in der Automation* (pp. 28-39). Springer Vieweg, Berlin, Heidelberg.
28. Da Xu, L., He, W., & Li, S. (2014). Internet of things in industries: A survey. *IEEE Transactions on industrial informatics*, *10*(4), 2233-2243.
29. Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. *Future generation computer systems*, *29*(7), 1645-1660.
30. Lee, J., Bagheri, B., & Jin, C. (2016). Introduction to cyber manufacturing. *Manufacturing Letters*, *8*, 11-15.
31. Maier, M., Chowdhury, M., Rimal, B. P., & Van, D. P. (2016). The tactile internet: vision, recent progress, and open challenges. *IEEE Communications Magazine*, *54*(5), 138-145.
32. Gellersen, H. W., Schmidt, A., & Beigl, M. (2002). Multi-sensor context-awareness in mobile devices and smart artifacts. *Mobile Networks and Applications*, *7*(5), 341-351.
33. Henningsen, S., Dietzel, S., & Scheuermann, B. (2018). Misbehavior Detection in Industrial Wireless Networks: Challenges and Directions. *Mobile Networks and Applications*, 1-7.
34. Meshram, A., & Haas, C. (2017). Anomaly detection in industrial networks using machine learning: a roadmap. In *Machine Learning for Cyber Physical Systems* (pp. 65-72). Springer Vieweg, Berlin, Heidelberg.
35. Fettweis, G., & Alamouti, S. (2014). 5G: Personal mobile internet beyond what cellular did to telephony. *IEEE Communications Magazine*, *52*(2), 140-145.
36. Simsek, M., Aijaz, A., Dohler, M., Sachs, J., & Fettweis, G. (2016). 5G-enabled tactile internet. *IEEE Journal on Selected Areas in Communications*, *34*(3), 460-473.
37. Gregori, F., Papetti, A., Pandolfi, M., Peruzzini, M., & Germani, M. (2017). Digital manufacturing systems: a framework to improve social sustainability of a production site. *Procedia CIRP*, *63*, 436-442.
38. Hygge, S., & Knez, I. (2001). Effects of noise, heat and indoor lighting on cognitive performance and self-reported affect. *Journal of Environmental Psychology*, *21*(3), 291-299.
39. Renaud, K., & Van Biljon, J. (2008, October). Predicting technology acceptance and adoption by the elderly: a qualitative study. In *Proceedings of the 2008 annual research conference of the South African Institute of Computer Scientists and Information Technologists on IT research in developing countries: riding the wave of technology* (pp. 210-219). ACM.
40. Davis, F. D. (1993). User acceptance of information technology: system characteristics, user perceptions and behavioral impacts. *International journal of man-machine studies*, *38*(3), 475-487.
41. Röcker, C. (2010). Social and Technological Concerns Associated with the Usage of Ubiquitous Computing Technologies. *Issues in Information Systems*, 11(1), pp. 61 - 68.
42. Holzinger, A., Searle, G., & Wernbacher, M. (2011). The effect of previous exposure to technology on acceptance and its importance in usability and accessibility engineering. *Universal Access in the Information Society*, *10*(3), 245-260.
43. Holzinger, K., Mak, K., Kieseberg, P., & Holzinger, A. (2018). Can we trust Machine Learning Results? Artificial Intelligence in Safety-Critical decision Support. *ERCIM NEWS*, (112), 42-43.

44. Holzinger, A., Biemann, C., Pattichis, C. S., & Kell, D. B. (2017). What do we need to build explainable AI systems for the medical domain?. *arXiv preprint arXiv:1712.09923*.
45. Levinson, A. R. (2008). Industrial justice: Privacy protection for the employed. *Cornell JL & Pub. Pol'y*, *18*, 609.
46. Kovach, D., Kenneth, A., Jordan, J., Tansey, K., & Framiñan, E. (2000). The balance between employee privacy and employer interests. *Business and Society Review*, *105*(2), 289-298.
47. Nord, G. D., McCubbins, T. F., & Nord, J. H. (2006). E-monitoring in the workplace: privacy, legislation, and surveillance software. Communications of the ACM, 49(8), 72-77.
48. Kaupins, G., & Minch, R. (2005, January). Legal and ethical implications of employee location monitoring. In System Sciences, 2005. HICSS'05. Proceedings of the 38th Annual Hawaii International Conference on (pp. 133a-133a). IEEE.
49. Liu, H., Darabi, H., Banerjee, P., & Liu, J. (2007). Survey of wireless indoor positioning techniques and systems. IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), 37(6), 1067-1080.
50. Sack, O., Röcker, C. (2013). Privacy and Security in Technology-Enhanced Environments: Exploring Users' Knowledge about Technological Processes of Diverse User Groups. In: *Universal Journal of Psychology*, 1(2), pp. 72 - 83.
51. Röcker, C., & Feith, A. (2009). Revisiting Privacy in Smart Spaces: Social and Architectural Aspects of Privacy in Technology-Enhanced Environments. In: *Proceedings of the International Symposium on Computing, Communication and Control* (ISCCC'09), pp. 201 - 205.
52. Funk, M., Bächler, A., Bächler, L., Korn, O., Krieger, C., Heidenreich, T., & Schmidt, A. (2015, July). Comparing projected in-situ feedback at the manual assembly workplace with impaired workers. In *Proceedings of the 8th ACM International Conference on PErvasive Technologies Related to Assistive Environments* (p. 1). ACM.
53. Falzon, P. (2005, December). Ergonomics, knowledge development and the design of enabling environments. In *Humanizing Work and Work Environment Conference* (pp. 10-12).
54. Villani, V., Sabattini, L., Czerniak, J. N., Mertens, A., Vogel-Heuser, B., & Fantuzzi, C. (2017). Towards modern inclusive factories: A methodology for the development of smart adaptive human-machine interfaces. *arXiv preprint arXiv:1706.08467*.
55. Nee, A. Y., Ong, S. K., Chryssolouris, G., & Mourtzis, D. (2012). Augmented reality applications in design and manufacturing. *CIRP Annals-manufacturing technology*, *61*(2), 657-679.
56. Lauber, F., & Butz, A. (2013, October). Are hmds the better huds?. In *Mixed and Augmented Reality (ISMAR), 2013 IEEE International Symposium on* (pp. 267-268). IEEE.
57. Cook, A. M., & Polgar, J. M. (2014). *Assistive Technologies-E-Book: Principles and Practice*. Elsevier Health Sciences.
58. Korn, O., Funk, M., & Schmidt, A. (2015). Assistive systems for the workplace: Towards context-aware assistance. *Assistive Technologies for Physical and Cognitive Disabilities*, 121-133.
59. Korn, O. (2012, June). Industrial playgrounds: how gamification helps to enrich work for elderly or impaired persons in production. In *Proceedings of the 4th ACM SIGCHI symposium on Engineering interactive computing systems* (pp. 313-316). ACM.
60. http://www.gesetze-im-internet.de/bitv_2_0/BJNR184300011.html