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An Adaptive Virtual Training System Based on Universal Design

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Abstract: The increasing complexity of manufacturing environments requires effective training systems to prepare the operation personnel for their tasks. Several training systems have been proposed. A common approach is the application of virtual environments to train interactions with an industrial machine in a safe, attractive, and efficient way. However, these training systems cannot adapt to the requirements of an increasingly diversified workforce. This paper introduces an approach for the design of an adaptive virtual training system based on the idea of universal design. The system is based on a two-step approach that consists of an initial adaptation to the user capabilities and real-time adaptations during training based on measurements of the user. The adaptations concern the use of different representations of lessons with different complexity and interaction modalities. The proposed approach provides a flexible training system that can adapt to the needs of a broad group of users.

Keywords: Human-machine interface, training, virtual reality, assembly, man-machine systems.

1. INTRODUCTION

The increasing complexity of industrial environments reinforces the necessity of effective training systems for the employees. A common approach is the application of virtual environments to teach maintenance or assembly procedures. Such approaches provide attractive, safe, cost-efficient and flexible ways to acquaint the operation personnel of machines with the required skills and procedures. Different research projects validated the benefits of these systems.

The diversification of the workforce regarding age or education caused by the demographic change challenges existing training systems. Training systems have to serve users with increasingly diverse capabilities. The interaction modalities or the complexity of the lessons have to be adapted to individual users to provide satisfying and effective training. Providing a system that is inherently accessible to diverse users is the aim of *universal design* that motivates the approach that is proposed in this paper (Story *et al.*, 1998). Existing training systems do not provide these capabilities for adaptation.

This paper proposes an adaptive virtual training system. A model with three components is introduced to describe the adaptations (*interaction*, *presentation*, and *complexity*). The training system adapts its characteristics to the user's constitution, disposition, and qualification. The training is adapted based on feedback that is collected during the training to address the state of the trainee.

2. UNIVERSAL DESIGN

The training system should be accessible to different users. The idea of universal design was therefore chosen as the foundation of the design process. Universal design demands the equal usability of a design for users with different capabilities and experience (Story *et al.*, 1998). The following section summarizes the seven principles of universal design according to Story *et al.* (1998). Section 2.2 derives five requirements for adaptive and accessible training systems.

2.1 Principles of Universal Design

The following seven principles for universal design have been proposed by Story *et al.* and were considered to develop the requirements for the training system.

1. *Equitable Use* ensures that different users can access the system without stigmatization.
2. *Flexibility in Use* ensures that the system can be adapted to the user, for instance by different interaction modalities.
3. *Simple and Intuitive Use* requires that the system avoids unnecessary complexity.
4. *Perceptible Information* requires that information is provided in different forms that can be perceived by users with different perceptive capabilities.

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5. *Tolerance for Error* requires that the design reduces the likelihood and the impact of errors.
6. *Low Physical Effort* requires that the interactions are carried out in a physically neutral position.
7. *Size and Space for Approach and Use* requires that the system meets the physical capabilities of the user.

2.2 Requirements for an Adaptive Training System

Following these principles, the authors have developed five requirements for adaptive training systems. Meeting these requirements ensures that the training system matches the ideas of universal design.

- **Multimodality (R1).** The training system has to offer different in- and output modalities. Providing different ways to interact with and to perceive a lesson addresses principles 1, 2, 4, and 7.
- **Performance-based Adaptation (R2).** The training system has to recognize the performance of the user and adapt accordingly. This addresses principles 1 and 5.
- **User Model (R3).** The training system is adapted based on a dynamic user model that describes her or his capabilities, knowledge level, and current workload. This addresses all principles.
- **Adaptive Representation (R4).** A lesson can be represented in different ways, for instance using visual, verbal, or haptic presentation. Adapting the representation addresses principles 1, 2, and 4.
- **Adaptive Structure (R5).** The content, length, and structure of the lesson should be adaptable to provide lessons with different levels of abstraction and length. Adapting the structure addresses principle 3.

3. STATE OF THE ART

This section discusses the state of the art of virtual training systems with a focus on adaptation. A comparison of the requirements (see Section 2.2) with the surveyed training systems concludes this section and motivates the addressed research questions.

3.1 Virtual Training Systems

The user of a virtual training system wants to learn an industrial procedure. Learning describes the achievement of a state that is characterized by a change of skills, knowledge or behavior (Hirst, 2006). Simulation is crucial when learning potentially dangerous skills or in prototypical stages of product development. The motivations for virtual training systems include their attractiveness and cost savings due to the lower consumption of equipment and a lower demand for trainers (Ponder *et al.* (2003)).

Industrial applications of virtual training system include the training of assembly or maintenance procedures. Brough *et al.* (2007) present a training system that provides different representation of a procedure that can be selected by the user (e.g., videos or 3D-animations). Ordaz *et al.* (2015) evaluate a system for automotive assembly where users place the components using gesture-based interaction. The training systems of Bhatti *et al.* (2012) and Gutiérrez *et al.* (2010) introduce haptic interaction to improve the effectiveness of the training of manual assembly procedures. Studies indicate that virtual training systems are an effective addition to traditional training methods.

3.2 Adaptive Training Systems

An adaptive system changes automatically based on observations of or knowledge about the user (Dix *et al.*, 2004). The system of Bluemel *et al.* (2003) allows reducing the amount of explanations to a state where the user has to execute the procedure by her- or himself. A similar approach is described by Gutiérrez *et al.* (2010). The system integrates different representation and interaction techniques to support the different stages of the knowledge acquisition process. Providing adaptive training supports the transfer of knowledge to the real environment and reduces the dependency on the training system.

3.3 Discussion and Problem Statement

Table 1 compares the surveyed training system with the requirements that were developed in Section 2.2. The surveyed training systems apply different in- and output modalities. However, only few systems pursue a multimodal approach (R1, R3). None of the training systems adapts based on the characteristics and the behavior of individual users (R2, R3). The training systems display error messages, but do not propose alternative approaches to teach the procedure if one approach was unsuccessful (R2). No adaptation of the presentation of lessons is provided (R4, R5). An integrated approach to address the increasingly diversified workforce with adaptive training is therefore missing.

Table 1. Comparison of the state of the art with the requirements for universal design (✓ = requirement addressed, ✗ = requirement not addressed).

	R1	R2	R3	R4	R5
Bluemel *et al.* (2003)	✗	✗	✗	✗	✓
Brough *et al.* (2007)	✓	✗	✗	✓	✗
Gutiérrez *et al.* (2010)	✓	✗	✗	✓	✗
Ordaz *et al.* (2015)	✗	✗	✗	✗	✗
Loch and Vogel-Heuser (2017)	✓	✗	✗	✗	✓
Proposed approach	✓	✓	✓	✓	✓

This paper introduces an adaptive virtual training system that addresses the needs of different user groups based on the idea of universal design. Its approach contains an initial adaptation to the constitution, disposition, and qualification of the user and iterative adaptations during training.

4. CONCEPT FOR AN ADAPTIVE TRAINING SYSTEM

The following section introduces the adaptive training system by describing the structure of the procedures and the adaptation mechanisms. The procedures are described using a two-level model. The lower level represents single actions (e.g., pressing a button). The upper-level describes an intermediate goal of several lower-level actions (e.g., restarting the machine).

The lesson is characterized by the in- and output modalities and the content. Different combinations of these components yield lessons with different degrees of realism and complexity. These parameters are derived with a two-step approach. An initial adaptation determines the initial configuration. It is based on static characteristics that are determined a-priori (e.g., constitution, disposition, or qualification). Iterative adaptations are proposed based on the feedback of measurements during the training. One measurement that allows detecting the state of the user is eye tracking data.

Initial adaptation is determined before the first use of the system. The user characteristics that affect this step are diverse. One approach to classify user's abilities with regard to limitations considers performance as a measurable output of user characteristics (Luczak, 1989). Luczak describes four dimensions of performance: constitutional, dispositional, adaptable characteristics, and qualification and competence. Constitutional characteristics (e.g., gender) cannot be changed. Dispositional characteristics (e.g., personality) change in a lifetime. Qualification and competence (e.g., education or knowledge) can be influenced and developed by individual performance. Adaptation characteristics (strain, fatigue, motivation and mood) depend on the situation. All characteristics determine the individual performance of a work task, which is characterized by its variability, even for one individual (Luczak, 1989). Initial adaption should consider the user characteristics that are relevant for a use case. It determines the features of input devices that matches the needs of the user. Similarly, the information presentation is adapted

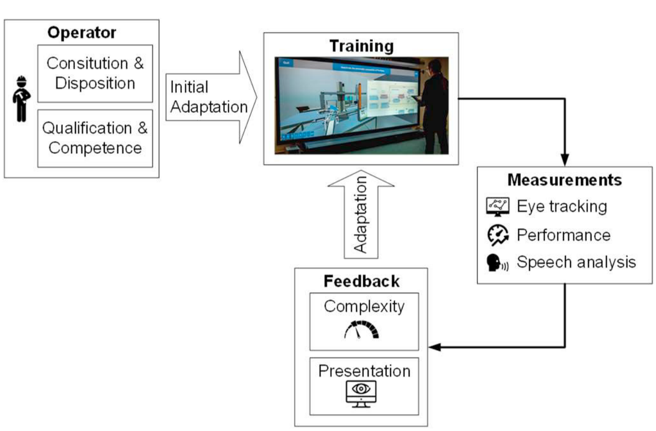

Fig. 1. Approach for the adaptation of the training system.

to the user according to three information processing stages: perception, cognition and action (Luczak, 1975). Fig. 1 summarizes how different measurement techniques and sources of knowledge are used to derive adaptations.

To describe the adaptation of the lessons, a model that formalizes their characteristics is necessary. This model is introduced in Section 5 and provides the foundation for the adaptation mechanisms.

5. CHARACTERISTICS OF A LESSON

The characteristics of a lesson are separated into three aspects. These are the *interactivity*, the *presentation*, and the *content*. Modifying these characteristics yields lessons with different complexity and realism.

5.1 Interaction

Interaction describes how the user communicates with the training system. Modifying this aspect allows providing the user with an input modality that fits her or his capabilities. Users with declines in motor capabilities, for instance, can use a speech-based interface. Simple interaction modalities (e.g., keyboard) can address users with low computer literacy. The work steps of the trained procedure also affect this aspect. User interface manipulations require a visual interaction modality (e.g., a touchscreen).

5.2 Presentation

Presentation describes how the training system communicates with the user. The visual modality has a critical role in most training systems. Visual information indicate the location where operations need to be done. Verbal information concerns textual descriptions of work steps. Modifying the characteristics of the presentation allows adapting the training system to the needs of the users. The font size or the color scheme can be adapted to support users with decreased vision. Similar adaptations could be done for verbal presentation, for instance by changing the playback volume of spoken information output. Multiple output modalities facilitate the adaptation of the system to vulnerable user groups.

5.3 Content

Content describes which information the training system provides about a work step. Instructions can be combined to functional groups with increasing levels of abstraction. The aggregation of work steps to groups can be visualized to facilitate the formation of correct mental models. Information, for instance the necessary tools, can be removed from the instructions if the user is already aware of them.

Three rules can be considered to adapt the content of the training system to the user's capabilities. *Information selection* prescribes that the quantity and the kind of information that is presented to the user is selected by the system, based on her or his cognitive status. Specifically, in the presence of cognitive difficulties (e.g., by incurring stress or low experience), the amount of data that is shown to the user needs to be reduced and information should be pre-processed (e.g., aggregated data, averaged data, or merged data). Consequently, it becomes easier for the user to recognize and understand the most relevant information. *Guidance* consists in providing the user with proper guidance procedures assisting her or him when long sequences of operations must be completed. Guidance, for example, can provide suggestions when decisions have to be made, indicating the next action to be performed, or providing a complete list of activities to be fulfilled. *Functionality enabling* consists in simplifying the training scenario, by reducing the number of available functionalities and operating modes. Table 2 summarizes how these rules are used for the tasks of the considered procedures.

Table 2. Summary of the content adaptation rules.

	Manual tasks	User interface	Inspection
Information selection	×	✓	✓
Guidance	✓	✓	✓
Functionality enabling	×	×	✓

6. REPRESENTATION OF LESSONS

The following section describes the realization of the training system. First, the components of the overall training system are introduced (see Section 6.1). Section 6.2 introduces the components that provide the lessons called *instruction providers*. These components provide lessons with different characteristics as discussed in Section 5. The instruction providers are chosen based on the characteristics of the user.

6.1 Components of the Training System

The lessons are based on a model that specifies the procedure and a structuring into sub-steps. It is stored in the central component, the *lesson controller*. The controller activates the instruction providers that represent the lessons and sends the model of the present user. The adaptations of the presentation and the interaction are carried out by the instruction provider. *Instruction providers* are different ways to represent a lesson. They are characterized by interaction modalities, presentation techniques, and the content as introduced in Section 5. The same content can be represented by different instruction providers to provide lessons with different characteristics.

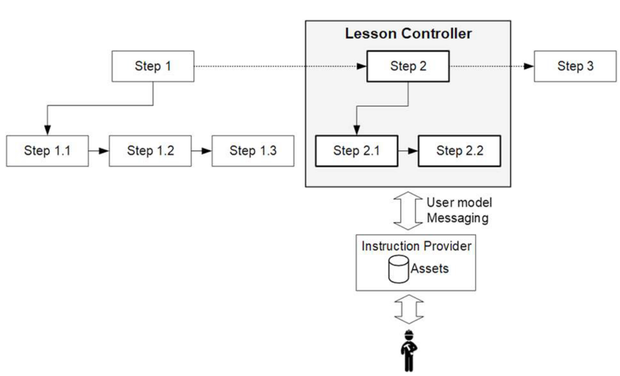

Fig. 2. Architecture of the adaptive virtual training system.

The *instruction providers* are decoupled from the lesson controller. The communication is handled via a technology-independent TCP-connection to support different platforms and devices. The lesson controller activates an instruction provider by a message that indicates the current step and the user model. The user interacts with the instruction providers. When the lesson is completed, the instruction provider sends a message to the lesson controller. The lesson controller can then activate the same – or a different – instruction provider to display the next part of the procedure. Fig. 2 summarizes the components of the proposed system architecture. Exemplary instruction providers are introduced in the following section.

6.2 Instruction Providers

An instruction provider delivers a specific representation of a procedure. Such representations may be the abstract display of the structure of the procedure (see Fig. 3) or immersive approaches to practice manual procedures (see Fig. 5). The selection of an instruction provider determines the level of complexity and realism of the training. It is therefore proposed to use a progression of instruction providers for a gradual increase of difficulty.

High-level Structure

This instruction provider gives an overview of the upper-level steps of a procedure (see Fig. 3). Providing such information should support the formation of a correct mental model (Gavish *et al.*, 2011). The user can select a step to display the sub-steps of this step. A consistent color scheme supports the retention of the procedure and shows the functional groups.

Alternative modalities are offered to support users with limitations. Speech commands allow navigating between the steps. The textual instructions can be replaced by graphical instructions to assist users with low literacy. As additional support to users with vision impairments, the visualization can be adapted with contrast enhancement and font size increasing.

This instruction provider has a low complexity since the information is aggregated to functional groups and only little interaction is expected. The presentation is abstract. Therefore, this provider can serve as the introduction to a procedure.

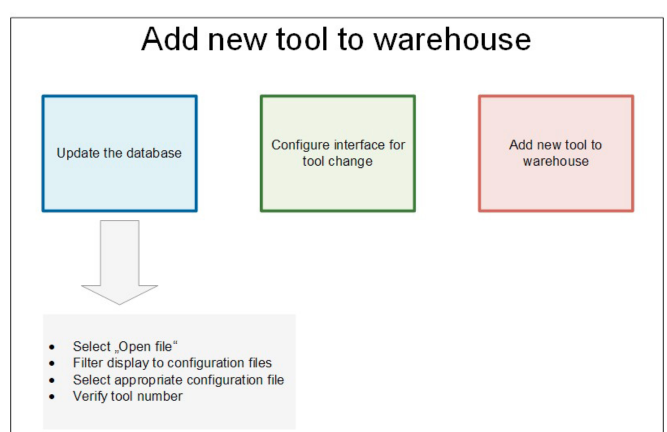

Fig. 3. Instruction provider that displays the structure of the procedure with a high contrast color scheme.

Fig. 4. Instruction provider that represents the procedure on a three-dimensional machine model.

Three-dimensional machine model

This instruction provider uses a three-dimensional model of the targeted machine to indicate the types and the locations of actions (see Fig. 4). This providers covers the composition of the whole machine and the sequence of the work steps.

The step list on the side provides all instructions of the procedure. The current instruction is also provided at the top of the screen. Visual indications display the locations of the steps at the machine and the required tools. The user can navigate the procedure linearly. Different output modalities, keyboard, mouse, and speech interaction, are offered. The presentation of the instructions can be adapted to the perceptive capabilities of the user, for instance by providing a color scheme with higher contrast as displayed in Fig. 4. The user can move around the machine using different navigation techniques. This allows providing an idea of the locations of the steps and of the structure of the machine. The user can furthermore walk around the displayed machine.

This instruction provider has a higher complexity since a visual representation is introduced and the content is concrete.

Manual Operation

This instruction provider allows practicing manual procedures with physical tools. This allows getting acquainted with the characteristics of manual procedures in virtual training. Due to the high level of user interaction, the user acquires important motor skills and practices bi-manual coordination. The procedural instructions are projected on a table in front of the user (see Fig. 5). The tools for the procedure and the components are highlighted.

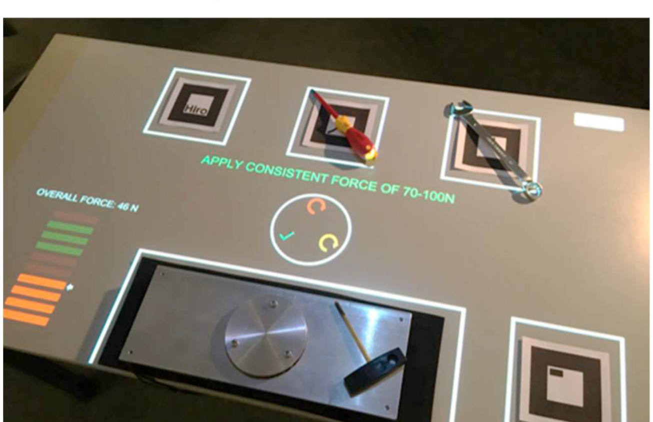

Fig. 5. Instruction provider for manual steps.

The user picks the tool and executes the instruction. The workpiece is equipped with force sensing resistors to detect when the user has correctly tightened a connection. Real-time feedback is provided on the work bench to support the user on how much force she or he needs to apply with the tools. When the training has been completed, the instruction provider sends a message to the training system server and the next step can be displayed. This instruction provider provides high complexity and realism.

7. REAL-TIME ADAPTATION

The system adapts based on performance measurements. These measurements assess whether the user can follow the lesson. This mechanism closes the feedback loop to allow iterative improvements of the training system. Fig. 6 summarizes the adaptation mechanisms.

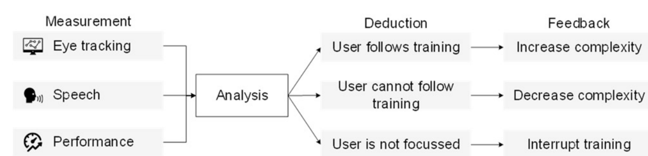

Fig. 6. Approach for real-time adaptation.

7.1 *Measurement*

Based on the analysis of measurements, it is deducted whether the user can follow the training. Feedback to adapt the training is provided based on these deductions. The following measurements are proposed.

- *Eye tracking* deducts the state of the user using pupil size and the gaze point. The data can be analyzed for specific patterns. If the system offers different presentation (e.g., visual and verbal), gaze patterns may indicate whether the user prefers a techniques.
- By *analyzing features in the voice* of the user, a classifier can be trained to assign a speech signal to emotional or stressful states. The complexity could be reduced if strain is detected.
- The amount of *time* that a user spends on each step of the training is another measurement. If a step takes longer than a threshold or than previous tries, this could indicate problems.

7.2 *Deduction*

The analysis of the measurements motivates deductions about the state of the user. These deductions indicate whether adaptations to the training system are required. Three deductions are discussed below.

- *The user can follow the training.* This deduction is made when the user completes the lesson below a time and error threshold and when measurements indicate that the user is focused on the training.

- *The user cannot follow the training.* This deduction is made when the user cannot finish steps or commits errors. This hypothesis is supported if the results of the speech analysis show negative emotions or if the analysis of the eye tracking indicates that the user is gazing randomly.

- *The user does not follow the training.* This hypothesis is motivated by slower actions of the user in comparison with previous trials. Eye tracking can support this hypothesis. Such data may indicate that the user is not focusing on the training system.

Further deductions can be considered if they can be reliably distinguished with the available measurement techniques.

7.3 Feedback

Feedback is created based on the deductions that the previous section introduced. Feedback motivates changes to the training system, for instance to the presentation and the content.

If the *user can follow the training,* the complexity can be increased to provide more realistic training. If the *user cannot follow the training.* Further measurements can define the adaptation of the system. If the eye tracking data indicates that the user focusses on a specific part of the display, it can be concluded that this aspect is causing trouble. If t*he user does not follow the training* the system suggests interrupting the training. The user can be asked to provide feedback and indicate whether the complexity should be in- or decreased.

8. CONCLUSIONS

This paper presented an adaptive virtual training system that adapts to the user based on the idea of universal design. The approaches provides initial before and real-time adaptations during training. The presented system can support the inclusion of vulnerable user groups in industrial environments.

Empirical evaluations of the system are planned to validate the expected benefits. The evaluations should compare adapted and non-adapted training systems to evaluate the benefits of the adaptations. Several representative scenarios have been developed for the INCLUSIVE research project (Sabattini *et al.* (2018)). The benefits of the proposed training system on its own and in combination with the other modules of the project will be evaluated using subjective and objective measurement techniques.

ACKNOWLEDGEMENTS

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REFERENCES

Bhatti, N.S., Khoo, Y.B., Creighton, D., Anticev, J. and Zhou, M. (2012), "Haptically Enable Interactive Virtual Assembly training System Development and Evaluation" in *Proceedings of the 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*.

Bluemel, E., Hintze, A., Schulz, T., Schumann, M. and Stuering, S. (2003), "Virtual environments for the training of maintenance and service tasks" in *Proceedings of the 2003 Winter Simulation Conference,* IEEE, pp. 2001-2011.

Brough, J.E., Schwartz, M., Gupta, S.K., Anand, D.K., Kavetsky, R. and Pettersen, R. (2007), "Towards the development of a virtual environment-based training system for mechanical assembly operations", *Virtual Reality*, Vol. 11 No. 4, pp. 189–206.

Dix, A., Finlay, J., Abowd, G.D. and Beale, R. (2004), *Human-computer interaction*, Pearson/Prentice Hall.

Gavish, N., Gutierrez, T., Webel, S., Rodriguez, J. and Tecchia, F. (2011), "Design Guidelines for the Development of Virtual Reality and Augmented Reality Training Systems for Maintenance and Assembly Tasks", *BIO Web of Conferences*, Vol. 1, p. 29.

Gutiérrez, T., Rodríguez, J., Vélaz, Y., Casado, S., Suescun, A. and Sánchez, E.J. (2010), "IMA-VR: A multimodal virtual training system for skills transfer in Industrial Maintenance and Assembly tasks", in *2010 IEEE RO-MAN, Viareggio, Italy*, IEEE, pp. 428–433.

Hirst, P.H. (2006), "What is Teaching?", *Journal of Curriculum Studies*, Vol. 3 No. 1, pp. 5–18.

Loch, F. and Vogel-Heuser, B. (2017), "A virtual training system for aging employees in machine operation", in *2017 IEEE 15th International Conference on Industrial Informatics (INDIN), Emden, Germany*, IEEE, pp. 279–284.

Luczak, H. (1975), "Untersuchungen informatorischer Belastung und Beanspruchung des Menschen", *VDI-Zeitschrift*, H 02 No. 10.

Luczak, H. (1989), "Wesen menschlicher Leistung", in *Arbeitsgestaltung in Produktion und Verwaltung*, Wirtschaftsverlag Bachem, Köln, pp. 39–64.

Ordaz, N., Romero, D., Gorecky, D. and Siller, H.R. (2015), "Serious Games and Virtual Simulator for Automotive Manufacturing Education & Training", *Procedia Computer Science*, Vol. 75, pp. 267–274.

Ponder, M., Herbelin, B., Molet, T., Schertenlieb, S., Ulicny, B., Papagiannakis, G., Magnenat-Thalmann, N. and Thalmann, D. (2003), "Immersive VR Decision Training: Telling Interactive Stories Featuring Advanced Virtual Human Simulation Technologies", in *EGVE '03 Proceedings of the workshop on Virtual environments 2003*, ACM, New York, NY, USA, pp. 97–106.

Sabattini, L., Villani, V., Czerniak, J., Loch, F., Mertens, A., Vogel-Heuser, B. and Fantuzzi, C. (2018), "Methodological Approach for the Evaluation of an Adaptive and Assistive Human-Machine System", in *2018 Proceedings of the 14th IEEE International Conference on Automation Science and Engineering (CASE),* IEEE (in press).

Story, M.F., Mueller, J.L. and Mace, R.L. (1998), *The Universal Design File: Designing for People of all Ages and Abilities*, The Center for Universal Design.