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Introduction and establishment of virtual training in the factory of the future

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In order to make the *factory of the future* vision a reality, various requirements need to be met. There is a need to continuously qualify the human worker about new and changing technology trends since the human is the most flexible entity in the production system. This demands introducing novel approaches for knowledge-delivery and skill transfer. This paper introduces the design, implementation and evaluation of an advanced virtual training system, which has been developed in the EU-FP7 project VISTRA. The domain of interest is automotive manufacturing since it is one of the leading industries in adopting future factory concepts and technologies such as *cyber-physical systems* and *internet of things*. First of all, the authors motivate the topic based on the state-of-the-art concerning training systems for manual assembly and relevant technologies. Then, the main challenges and research questions are presented followed by the design and implementation of the VISTRA project including its methodologies. Furthermore, the results of experimental and technical evaluation of the system are described and discussed. In the conclusion, the authors give an outlook at the implementation and evaluation of the example application in related industries.

Keywords: advanced interaction; digital factory; factory of the future; human-centred production; *Industry 4.0*; semantics; training systems; virtual reality

Introduction

The success of manufacturing enterprises depends on their capability to quickly adapt to technological, social and economic boundary conditions. The increasing product complexity, the wealth of product variants and the shorter product life cycles are challenges that can only be solved to a limited extent by traditional automation.

High product variability and shortened product life cycles require agile and flexible production structures which can be rapidly reconfigured and prepared for new customer demands. Many manufacturing sections such as the automotive industry cast off the idea of full automation and rather follow mass customisation strategies, which mean a combination of low unit costs of mass production processes and a maximum of flexibility for individual customisation. To address these new requirements, numerous (inter-) national innovation and roadmapping programmes have been developed across Europe, e.g. EFFRA (2012). Special emphasis deserves the German *Industry 4.0* innovation strategy which targets at the efficient, individual production at lot size 1 under the condition of highly flexibilised mass production by the emergence of *cyber-physical systems* and *internet of things* technologies in the production domain (Kagerman, Wahlster, and Helbig 2013). *Industry 4.0* foresees flexible, modular production equipment as well as self-configuring and self-optimising production processes (Loskyll et al. 2012). In addition, it incorporates the idea of full integration and continuity of data, e.g. horizontal integration through value networks, end-to-end integration of engineering across the product and production development process, and vertical integration within networked manufacturing systems.

The *Industry 4.0* innovation strategy is not gravitating towards worker-less production facilities (unlike the Computer Integrated Manufacturing approach of the 1980s): human operators are acknowledged as the most flexible parts in the production system being maximally adaptive to the more and more challenging work environment. The future requirements workers face on the shop floor are increased product complexity, shortened product development cycles and quickly changing production processes requiring fast adaption to new boundary conditions. In order to enable the human workers to fulfil their tasks efficiently within more and more complex environments, the implementation of adequate qualification measures is required comprising both the organisational and technological level.

The automotive industry is a technology pioneer, where key aspects of *Industry 4.0* are already realised. First, product and production development make extensive use of digital tools and methods for testing and securing production processes beforehand and are, to some extent, supported by advanced data integration and continuity (compare the *digital factory* concept; VDI 4499 2008). For instance, product designers and production planners exchange data continuously in order to optimally plan the configuration of the production line and to secure its

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ramp-up. Second, production lines in automotive feature a predefined versatility for multi-model and multi-variant production at high volume by combining advanced automation with the flexibility of manual work. For instance, in the area of final assembly qualified personnel in combination with automatised equipment create cars each consisting of typically 10,000 single parts or more.

Before the operators are allowed to perform the assembly in the production line, they must repeatedly practise the respective assembly processes. Workers train by the help of hardware prototypes going along with several disadvantages, e.g. it is costly, limited in scale and product variants, limited hardware availability only at a late development stage (Krammer, Neef, and Plapper 2011). To bypass the limitations of hardware training and especially to test and secure production processes already at an early stage *computer-aided technologies* for training purposes need to be developed and deployed in the existing IT and organisational infrastructures of the manufacturers. In this context, virtual training is a promising solution.

Virtual training was first introduced more than two decades ago (Kozak et al. 1993). Despite many studies that have confirmed the positive impact of virtual training on procedural learning in manual industrial tasks (Lin et al. 2002; Malmsköld et al. 2007; Adams, Klowden, and Hannaford 2001), virtual training has not made its way into daily practice in industry yet.

The first reason for the rare establishment of virtual training is the lack of user acceptance resulting from its design (Gorecky, Mura, et al. 2013). Existing virtual training solutions either represent desktop-based simulations using mouse interaction or expensive caves for simulating 3D virtual environments. Both approaches neglect convenient and affordable consumer market solutions like *Nintendo Wii* and *Microsoft Kinect*. Moreover, there is no elaborated training process that synergistically combines virtual training with hardware training and integrates it into the existing organisational structures.

The second reason for virtual training not being established in training practice is the fact that data relevant for virtual training are widespread over different systems throughout the company. Despite ongoing efforts on data integration, authoring efforts for collecting the relevant data, defining the training scenarios and preparing the training plans have outbalanced the potential benefits of virtual training. The precondition for the breakthrough of virtual training is generation of training scenarios requiring little or no authoring effort at all. Although data from the product and production development (e.g. structural and geometrical data on products and production structures, process descriptions) are available and could be used for this purpose, a methodology for integration and reuse of existing data structures is missing.

This paper presents the design and evaluation of an advanced virtual training system which addresses the mentioned problems. It has been developed in the EU-FP7 project VISTRA (http://www.vistra-project.eu) involving all relevant stakeholders. It covers a suitable methodology for the automated preparation of virtual training scenarios, i.e. by integrating relevant planning data from the distributed IT structures of the *digital factory*. Therefore, the project offers important implications for the *factory of the future* vision, concretely, a higher transparency of complex production processes for the human operator and an important strategic pillar to quickly adapt qualification profiles to new manufacturing requirements.

Related work

In this section, existing technologies, current concepts and future trends for advanced training applications are reviewed, and the two main challenges preventing virtual training from being adopted in automotive industry are further elaborated.

Relevant technologies and concepts

The use of technology allows some advantages over traditional learning methods. Learning can be individually adapted to the trainee, is independent concerning time and place, and takes place by aid of multimedia content (Zhang and Nunamaker 2003). Therefore, computer-based training is increasingly used to complement or replace traditional, non-computer-based learning methods like paper documents or physical setup.

Virtual reality (VR) has been explored and implemented in several commercial products, where a worker can review and explore a virtual product model. Examples are *nGrain*, or *Aerosim*'s, *Virtalis*' and *Simdustrial*'s virtual maintenance training systems. Moreover, there are a few virtual training applications for manufacturing processes like the *Vizendo* virtual training suite and the work of Brough et al. (2007). Drawbacks of these systems are the amount of effort needed to create training scenarios from heterogeneous data sources and the non-immersive user interaction through desktop-based concepts using traditional interaction devices like mouse and keyboard.

Recent progress in human–machine interaction is a prerequisite for the design of new advanced computer-based training systems. *Augmented reality* (AR) – the enrichment of the real world by virtual overlays – allows the combination of the actual work environment with additional virtual information. For instance, the *HoloDesk* setup (Hilliges et al. 2012) creates the illusion of direct interaction with virtual objects using an optical see-through display and gesture-based interaction by rendering a 3D scene through a half silvered mirror. Another line of work by Gorecky, Campos, et al. (2013) has demonstrated a concept for computer-assisted manual workstation. The system used a workflow recognition module that can detect whether the operations were carried out successfully in order to provide virtual instructions and guide the user step by step through the manual assembly process. Finally, wearable devices such as data glasses and head-mounted displays show great promise in VR/AR-based training. One example is *Oculus Rift*, a low-cost, immersive VR headset, projected for gaming purposes. *Google Glass* is an optical head-mounted display that displays information in a smartphone like hands-free format and allows seamless communication through natural voice commands, with the possibility of being programmed to use AR/VR technologies.

Furthermore, the success of advanced computer-based training systems depends on the used interaction possibilities which should – compared to traditional input devices – enable playful and natural exploration. For instance, people can go through an assembly in a virtual environment using hand movements, gestures or voice commands (see current commercial hardware like *Microsoft Kinect* and *LeapMotion*). Mobile technologies, such as smartphones and tablets, capture the context using sensors and cameras and offer adaptive services, i.e. information at the right place of action. Additionally, intelligent monitoring of human workflows can be incorporated with the use of on-body-sensors and cameras (see EU-FP7 project COGNITO; Gorecky, Worgan, and Meixner 2011). Their mobile training system builds up a system-internal understanding of the assembly process by observing expert users, and subsequently instructs less experienced users through comparison with the recorded workflow. User input and output has been realised via speech (compare *Apple's Siri* or *Google Voice Recognition*). Another output modality especially useful for realistic simulation of material handling is haptics. For instance, haptic feedback devices simulate the force required to fit a component, e.g. *Nintendo's WiiMote* which provides simple haptic feedback representing collisions of big forces or *INCA 6D*, a more expensive technology, offering sophisticated force feedback on all six degrees of freedom.

Finally, the success of advanced computer-based training systems depends on the effort and costs for the set-up and maintenance. Training content must be created and regularly updated. Instead of creating the training content from scratch, existing content sources in the enterprise can be (re-)used for the purpose of qualification. A potential source of training content lies in the *digital factory* concept (VDI 4499 2008). The digital factory defines methods, tools and models that support development and planning activities throughout the product life cycle. However, the effective range of the digital factory is currently limited to the group of the so-called 'white-collar workers', i.e. designers, product developers, production planners, etc. 'Blue-collar workers' on the shop floor who are not primarily concerned with planning activities do not or only indirectly benefit from the concept, although the digital factory with its extensive information and knowledge bases provides a huge potential for training applications. The models of the digital factory include, e.g. information about the product geometry and structure, the factory and workplace layout, and the production processes. This information is valuable for the respective planning task, but also for training content generation. Embedded in advanced computer-based training systems, the information finds a direct way to the operators on the shop floor.

Research questions

Challenge 1: training system design

The interaction design of the virtual training system influences user acceptance, knowledge transfer and the overall success of the system. The immersion and user involvement of desktop-based concepts using traditional interaction devices is low; the reason is that the interaction metaphor of mouse pointing and clicking does not match or resemble the corresponding task in the real world, e.g. manual assembly of a part. As shown previously, recent advances in delivery mechanisms are potentially reducing the costs while offering an enhanced user experience. In order to ensure a high user acceptance as well as a high effectiveness of virtual training, the challenge is to integrate these raising design and interaction opportunities into a deliberate training system design.

Moreover, adding a system into an existing organisational infrastructure might seem cumbersome to business owners requiring integration of training systems seamlessly into existing organisational systems without fundamentally altering them. New technologies and concepts make it possible to add a training system as an extra layer over the existing infrastructure. In order to ensure a high acceptance by users and management, the training system has to be integrated into existing processes appropriately.

Challenge 2: training content generation

The second major obstacle is the currently inefficient management of the data relevant to the virtual training. Ideally, virtual training scenarios should be created with minimal or no data authoring effort at all by tapping existing data sources. Usually enterprise data are spread over different systems in the company and are stored in different formats. So far, the efforts of collecting relevant data, building virtual training scenarios and defining training plans have surpassed the benefits of virtual training itself. Although the data from product and manufacturing design could be used for this purpose, there is no methodology for automated integration and reuse of existing data structures.

The challenge is to model the information structures in the digital factory in an open, modular and semantically expressive way, so that they can be dynamically aggregated for and used in the computer-based training systems. Meeting this challenge might incorporate semantic modelling (e.g. OWL), open and neutral data formats (e.g. STEP, JT) and data integration into the respective application via flexible and standardised interfaces (e.g. REST-ful web services).

Implementation of the VISTRA advanced virtual training system according to the factories of the future vision

VISTRA training system design (challenge 1)

Hardware for game-based user interaction

To address the first challenge of user involvement and acceptance, an innovative hardware set-up for game-based user interaction has been introduced. The main criteria influencing the decision of the hardware set-up were costs, scalability and user acceptance. In order to allow for a natural and more realistic interaction with the virtual objects and environment in the VISTRA system, the advantages of immersive user experience and large-scale training at reasonable costs have been combined – by using immersive, but out-of-the-shelf hardware set-ups (e.g. standard monitor for visualisation, *Microsoft Kinect* in combination with a *Nintendo Wii* device for interaction) (see Figure 1).

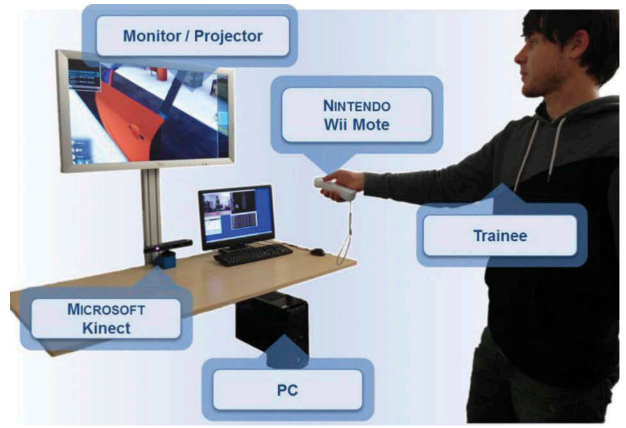

Figure 1. VISTRA hardware set-up allows for natural and realistic interaction.

Learning concept

As mentioned previously, several studies have proven that computer-based, virtual training has a positive effect on the procedural learning in manual, industrial tasks. The most relevant knowledge components are clustered in different semantic classes (compare Figure 2). Whereas virtual training is successful in communicating these training contents, the opportunities for motor skill development through virtual training are very limited (Jia, Bhatti, and Nahavandi 2009). Therefore, the VISTRA learning concept focuses on teaching relevant knowledge including involved objects (parts and tools), assembly positions, specific modality and sequence instead of fine motor skills.

Initial learning within the virtual training occurs in 'easy' mode involving maximal support to execute all assembly steps and with all parts and tools pre-given. This introduction focuses on familiarising with the training content. Afterwards, trainees move to medium and hard modes, where appropriate tools and parts have to be actively chosen, e.g. trainees select tools and components from a pop-up carousel-style menu. Furthermore, in mini games trainees strengthen their acquired knowledge in a playful and entertaining way.

The semantic classes of training and the content of training were elicited through task analysis (Kirwan and Ainsworth 1992) as part of the user-centred design approach. The results from task analysis within the VISTRA project (Hermawati et al. 2015) confirmed the classification in Figure 2. Detailed recommendations on how to integrate virtual training concepts into existing processes from an organisational perspective were

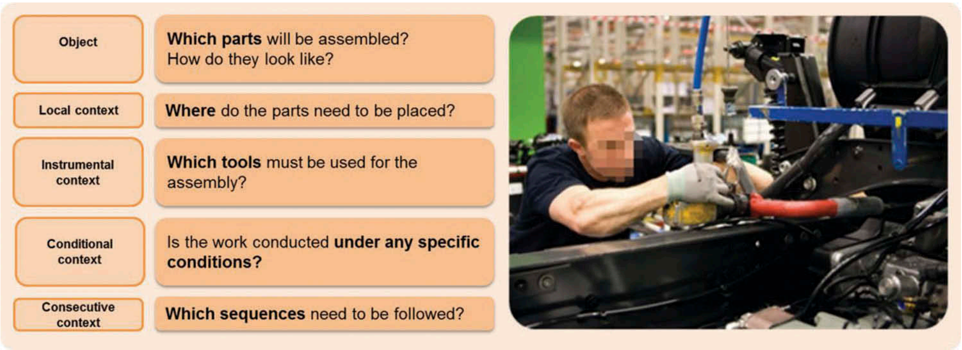

Figure 2. Overview about relevant semantic classes of training content for operator training in the automotive industry.

Table 1. Core concepts in the assembly process model.

Concept name	Description
Station	Is a defined working area, in which the operator performs a sequence of operations
Operation	Is an activity in which parts are added to a product (optional: position) with or without tools
Assembly Sequence	Defines the order in which an operation is performed
Activity	Is a description of an action, which must be performed by the operator
Tool	Is a manual or driven tool to assemble a part to the product
Part	Is a single part or assembly which will be assembled to the product
AssemblyPosition	Defines a place at the product where an operation has to be performed
Product	Is the object to be produced
Operator	Performs an activity

previously reported (Gorecky, Mura, et al. 2013). Amongst others, the authors noted the importance of acknowledging the roles of the trainers in the virtual training instead of cutting their competencies. This means that they steer and monitor the training process via a planning and evaluation tool containing training statistics for instance. If predefined learning goals are achieved, trainers decide if trainees pass over to hardware training where they deepen handling with the parts and their motor skills. Trainers receive better overview of training performances and a supporting tool for training planning. Another important regard is that organisations have to wise up their employees regarding the usage of data and security issues, and implement role-based access control.

Methodology for the automated generation of virtual training content (challenge 2)

To address an automated training content generation, the VISTRA training system incorporates an integration methodology based on a reference architecture for an interoperable information interface (Stork et al. 2012). The information interface merges heterogeneous enterprise data from planning processes in a unified information model that is provided as input to the virtual training application.

Up to now, there seems to be no attempt to represent assembly knowledge in a computer- and human-understandable way, although such a model can enable new applications, especially virtual training, and encourage knowledge sharing across the different stages of product and production engineering. The unified model must be able to embrace all relevant knowledge and assure its interoperable applicability. For its development, a semantic modelling approach based on ontologies was chosen due to its advantages over other information modelling approaches in terms of integration, derivation, verification and reuse of knowledge. Since ontologies allow computer algorithms to understand and reason about the contained information, knowledge can be represented according to the different stakeholders. Here, different scenarios are conceivable, e.g. a trainee needs interactive training instructions, the trainer wants to see the results of his/her training group, and a manufacturing engineer wants to test and compare different assembly variants, etc. However, which information concepts must be addressed in the unified model in order to enable these scenarios? Table 1 shows how assembly-related knowledge in the domain of automotive industry can be described in a common and consistent way by defining a simple set of concepts.

The development of the ontology followed the Methontology approach (Fernández-López, Gómez-Pérez, and Juristo 1997) which focuses on the acquisition of relevant knowledge already in early stages of development. The relevant concepts and modelling excerpts are deducted from interviews with expert from the end-users and document searches (e.g. standards and work sheets from the end-users).

Based on the introduced concepts, the VISTRA ontology for virtual assembly training has been built. Nevertheless, virtual training requires more information than just the description of assembly tasks. As shown in Figure 3, additional entities from different enterprise sources must be taken into consideration including

- station layout which is important to create an authentic representation of the actual work environment;
- success criteria (e.g. timing) which must be introduced to measure, if the execution of training was successful;
- team structures which must be reproduced in order to define the different roles and responsibilities (e.g. trainee, group leader, trainer, etc.); and
- feedback and statistical data which must be associated and stored in the training model for the purpose of training analyses and evaluation.

Figure 4 depicts a simplified excerpt of the VISTRA ontology for virtual training, which contains information

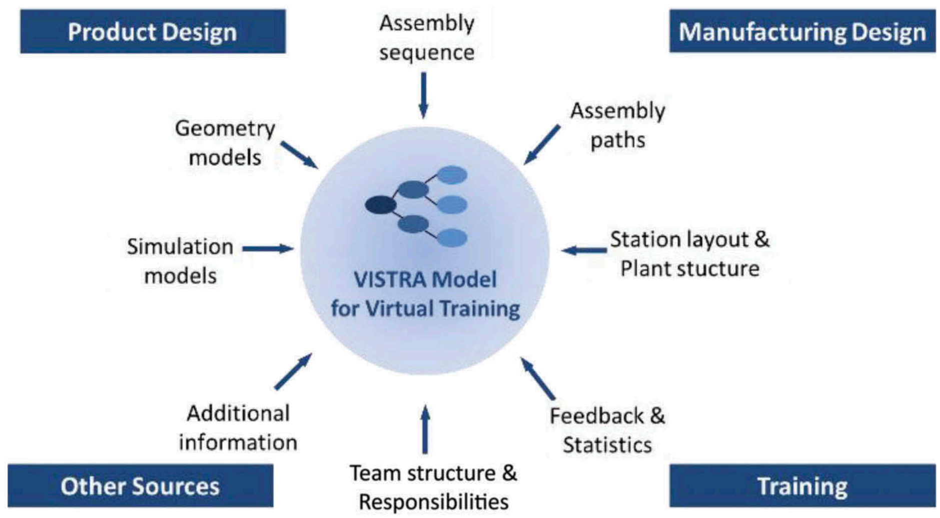

Figure 3. Input data from different sources of the VISTRA model for virtual assembly training.

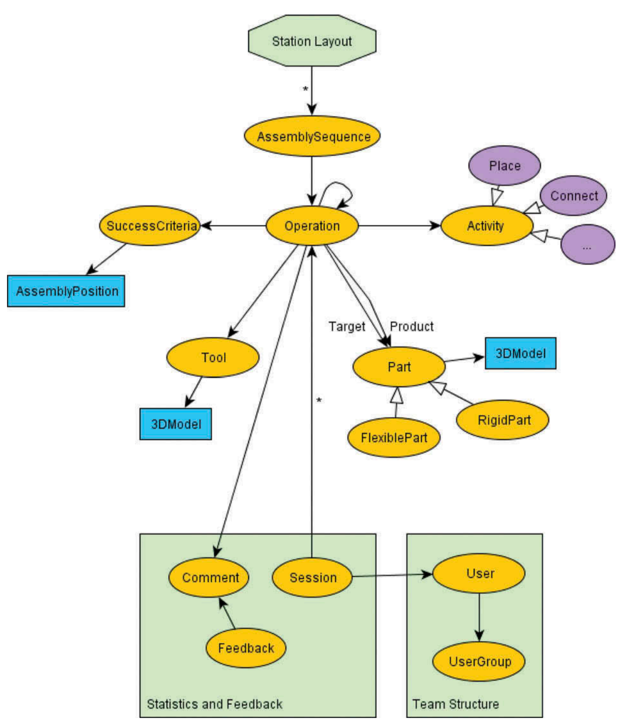

Figure 4. Simplified excerpt of the VISTRA ontology for virtual assembly training.

about the assembly processes (*Operation, Activity, Tool, Part* and *Assembly Sequence*), the team structure (*User* and *User Group*) and the statistics (*Comment, Feedback* and *Session*). Due to its modular character, the VISTRA ontology is open to be adapted and extended for further domains and use cases.

Ontologies are a well-suited technology for integrating information coming from several heterogeneous data sources. Syntactic and semantic conflicts which may occur during data integration are addressed by a procedure model which provides general guidance for the instantiation and implementation of the information interface (Gorecky 2014). The procedure model involves, amongst others, analysis of data sources and definition of transformation rules for the mapping from the existing data formats and terminologies to the unified VISTRA structure and terminology. By following the procedure model, enterprises can ensure an automated supply of planning data to virtual training application and thus that the application is always based on current and consistent data.

Overall VISTRA system architecture

In this section, the conceptual system architecture of the VISTRA training system is described. The system consists of three fundamental components (see Figure 5).

The first and central component of the VISTRA system is the *VISTRA Knowledge Platform* (VKP). It is responsible for building the bridge between the existing *digital factory* data and the virtual training as client application. The VKP receives enterprise data in various formats (e.g. XML, PLMXML) and transforms it to the VISTRA ontology (e.g. OWL) according to beforehand specified set of transformation rules (based on a Saxon-processor, XSLT and X-PATH). The transformed data are then ingested, stored and managed in a semantic framework. Therefore, OWLIM LITE as one of the most powerful semantic frameworks can be used. It can store up to 10 million RDF statements, while OWLIM SE with up to 10 billion RDF statements provides a more comprehensive, but also fee-based storage solution (ONTOTEXT AD 2014).

To set up a communication channel between VKP and client applications, a variety of technical possibilities

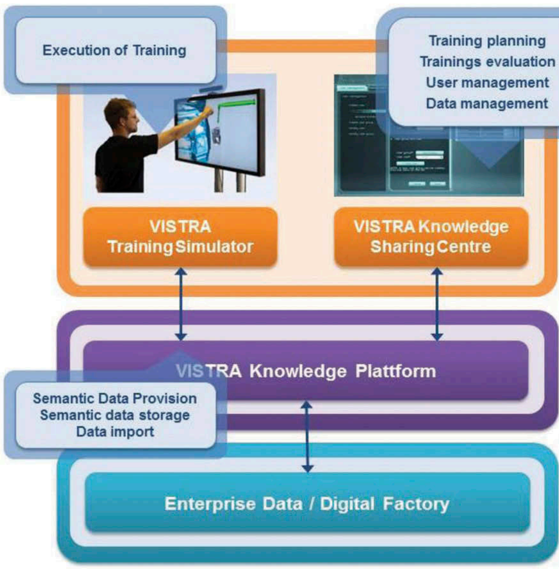

Figure 5. The VISTRA system architecture with its three main components.

exists, of which RESTful webservices were chosen. They offer significant advantages, i.e. openness, low implementation complexity and ability for loosely coupling which supports easy integration into existing IT system landscapes (in line with approaches such as service-oriented architecture and enterprise application integration). For basic data security, a user authentication using *HTTP Basic Authentication* and the TLS encryption protocol for data transmission were implemented.

The second component of the system is called *VISTRA Training Simulator* (VTS). The VTS module represents a UNITY 3D-based virtual assembly simulation where the virtual training is performed in an interactive and playful manner (see Figures 6 and 7). Training scenarios are loaded dynamically from the VKP considering available products, stations and assembly sequences, trainer guidelines and trainee profiles. Training results and feedback are

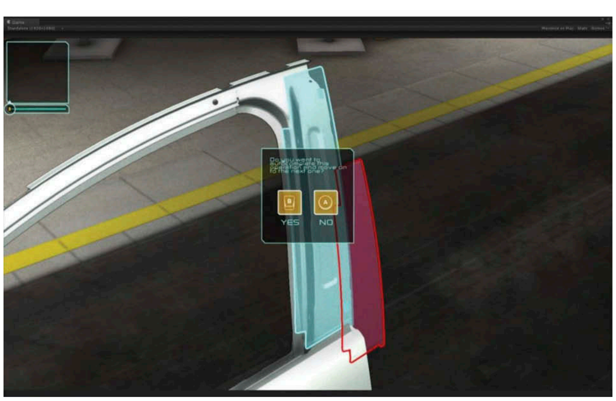

Figure 6. Screenshot of the VISTRA training simulator.

Figure 7. The inventory view from which the user chooses the tool to use (medium and hard modes).

written back to the VKP for further review and for improving training scenarios in future sessions.

Planning training sessions and reviewing training results are important tasks which trainers execute via the third system component, the *VISTRA Knowledge Sharing Centre* (VKSC). Furthermore, the VKSC module allows to check, edit and manually extend imported enterprise and user data, when necessary.

Case studies and evaluation

Evaluation of the usability and effectiveness of the VISTRA system

The complete VISTRA training system has been developed and implemented as a prototype at two automotive end-user sites. There, it has been tested in several user studies with close to 100 participants (Hermawati et al. 2015; Gorecky et al. 2012; Gorecky, Mura, et al. 2013; Langley et al., n.d.).

First, in the context of a user-centred approach, the current training processes were analysed and user requirements were formulated (Gorecky, Mura, et al. 2013; Gorecky et al. 2012). Usability evaluations and experiments supported the iterative development (Langley et al., n.d.) and demonstrated the effectiveness of the VISTRA training for learning new assembly operations.

Technical evaluation of the VISTRA methodology for the automated generation of training content

The integration methodology for VISTRA training system was fully implemented and validated under realistic conditions at two end-user sides. According to an internal study and compared to traditional authoring approaches, the integration methodology, which allows the reuse of existing planning data for qualification purposes, reduces the initial set-up time for a virtual training scenario (one car with around 1.200 operations) from more than 12 to 3 person-months. It must also be noted that after the initial implementation of VISTRA integration methodology new products which comply with the given information structure can be integrated 'on-the-fly' with almost no effort.

Overall, the internal technical evaluation has proven that the VISTRA integration methodology using semantic triple stores and webservices comply with the general requirements regarding performance, storage and data security in automotive industry and thus can be deployed in productive industrial environments.

Summary and outlook

In this paper, the design, implementation and evaluation of the VISTRA virtual training system were presented. Taking the automotive industry as an example, the challenges to develop qualification strategies were stated, and the technical approach in establishing virtual assembly training as a standard tool and method to support production ramp-up was discussed.

The first challenge was to assure user acceptance. It was shown that the game-based user interaction offers an engaging and intuitive user interface and increase user involvement and knowledge transfer. Second, the challenge of integrating existing heterogonous enterprise data sources, in order to build up the virtual training scenarios, was addressed by introducing a methodology for training content generation that is essentially based on semantic technologies to build up a computer-and-human-understandable model. Then the overall system architecture, enclosing the management of the training content and the build-up applications, was briefly described.

The VISTRA system is a complete solution for the automatic generation of diverse training content with no mandatory manual authoring stages (provided that the data structures are current, valid and rich in information, as is the case in the considered automotive scenarios). The basic data for the training experience are derived from the engineering systems of the enterprise itself, i.e. their *Product Lifecycle Management*. Afterwards, every aspect of the VISTRA training is automatically created without the need for experts or instructional designers. All aspects of the training are driven by the system itself, from the templates for the creation of training plans, to the instructional scaffolding ensuring the most effective transfer and retention of knowledge and development of skilled performance, clear communication of the results of training to the trainee, the possibility to train using games or to take tests, such that the overall experience is highly immersive and extremely simple to navigate.

Moreover, experimental evaluation took place throughout the project and confirmed the usability and effectiveness of the training system. The technical evaluation of the VISTRA methodology for training content generation showed that the proposed approach can be efficiently realised to overcome information-technical restriction still existing in many manufacturing enterprises. So far, only in limited cases manual authoring is required, e.g. to integrate the behaviour of handling tools and robots.

The VISTRA virtual training system as well as the VISTRA methodology for training content generation showed success in the automotive sector and exhibits a high potential to be integrated into other related industries with similar product complexity and production structures (e.g. aerospace and train industry).

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Adams, R. J., D. Klowden, and B. Hannaford. 2001. "Virtual Training for a Manual Assembly Task." *Haptics-e* 2 (2): 1–7.

Brough, J. E., M. Schwartz, S. K. Gupta, D. K. Anand, R. Kavetsky, and R. Pettersen. 2007. "Towards the Development of a Virtual Environment-Based Training System for Mechanical Assembly Operations." *Virtual Reality* 11: 189–206. doi:10.1007/s10055-007-0076-4.

EFFRA. 2012. *Factories of the Future PPP – FoF 2020 Roadmap – Consultation Document*. Luxemburg: European Factories of the Future Research Association. http://www.effra.eu/attachments/article/129/Factories%20of%20the%20Future%202020%20Roadmap.pdf

Fernández-López, M., A. Gómez-Pérez, and N. Juristo. 1997. "Methontology: From Ontological Art Towards Ontological Engineering." Proceedings of AAAI97 Spring Symposium Series, Workshop on Ontological Engineering, Stanford, CA, March 24–26.

Gorecky, D. 2014. *Entwicklung Einer Methodik Zur Informationstechnischen Integration Von Virtuellem Training*. Kaiserslautern: Technische Universität Kaiserslautern.

Gorecky, D., R. Campos, H. Chakravarthy, R. Dabelow, J. Schlick, and D. Zühlke. 2013. "Mastering Mass Customizations – A Concept for Advanced, Human-Centered Assembly." *Academic Journal of Manufacturing Engineering* 11 (2): 62–67.

Gorecky, D., G. Lawson, K. Mura, S. Hermawati, and M. L. Overby. 2012. "User-Centered Design of a Game-Based, Virtual Training System." In *Advances in Ergonomics in Manufacturing*, edited by W. Kamorowski, 78–87. Boca Raton, FL: CRC Press.

Gorecky, D., K. Mura, and F. Arlt. 2013. "A Vision on Training and Knowledge Sharing Applications in Future Factories." *Analysis, Design, and Evaluation of Human-Machine Systems* 12 (1): 90–97.

Gorecky, D., K. Mura, I. von Falkenhausen, J. Apold, and F. Arlt. 2013. "Spielebasiertes Training Gestalten Und

Integrieren – Eine Fallstudie Aus Der Automobilmontage." *Atp Edition* 55 (5): 888–895.

Gorecky, D., S. F. Worgan, and G. Meixner. 2011. "COGNITO: A Cognitive Assistance and Training System for Manual Tasks in Industry." Proceedings of the 29th Annual European Conference on Cognitive Ergonomics, Rostock, August 24–26, 53–56.

Hermawati, S., G. Lawson, M. D'Cruz, F. Arlt, J. Apold, L. Andersson, and L. Malmsköld. 2015. "Understanding the Complex Needs of Automotive Training at Final Assembly Lines." *Applied Ergonomics* 46 (A): 144–157.

Hilliges, O., D. Kim, S. Izadi, M. Weiss, and A. Wilson. 2012. "Holodesk: Direct 3d Interactions with a Situated See-Through Display." SIGCHI Conference on Human Factors in Computing Systems, Austin, TX, May 5–10, 2421–2430.

Jia, D., A. Bhatti, and S. Nahavandi. 2009. "Design and Evaluation of a Haptically Enable Virtual Environment for Object Assembly Training." IEEE International Workshop on Haptic Audio Visual Environments and Games, Lecco, November 7–8, 75–80.

Kagerman, H., W. Wahlster, and J. Helbig. 2013. *Securing the Future of German Manufacturing Industry: Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0, Final Report of the Industrie 4.0 Working Group*. Berlin: Forschungsunion im Stifterverband für die Deutsche Wirtschaft e.V.

Kirwan, B., and L. K. Ainsworth. 1992. *A Guide to Task Analysis: The Task Analysis Working Group*. London: CRC Press.

Kozak, J. J., P. A. Hancock, E. J. Arthur, and S. T. Chrysler. 1993. "Transfer of Training from Virtual Reality." *Ergonomics* 36: 777–784. doi:10.1080/00140139308967941.

Krammer, P., D. Neef, and P. Plapper. 2011. *Advanced Manufacturing Technologies for General Assembly*. SAE 2011 World Congress & Exhibition Technical Paper. doi:10.4271/2011-01-1253.

Langley, A., G. Lawson, K. Mura, S. Hermawati, and M. D'Cruz. n.d. "Establishing the Usability of a Virtual Training System for Assembly Operations within the Automotive Industry." *Human Factors and Ergonomics in Manufacturing & Service Industries*.

Lin, F., L. Ye, V. G. Duffy, and C. J. Su. 2002. "Developing Virtual Environments for Industrial Training." *Information Sciences* 140: 153–170. doi:10.1016/S0020-0255(01)00185-2.

Loskyll, M., I. Heck, J. Schlick, and M. Schwarz. 2012. "Context-Based Orchestration for Control of Resource-Efficient Manufacturing Processes." *Future Internet* 4 (4): 737–761. doi:10.3390/fi4030737.

Malmsköld, L., R. Örtengren, B. E. Carlson, and L. Svensson. 2007. "Preparatory Virtual Training of Assembly Operators: An Explorative Study of Different Learning Models." Proceedings of Swedish Production Symposium 2007, Gothenburg, August 28–30.

ONTOTEXT AD. 2014. OWLIM: http://www.ontotext.com/owlim

Stork, A., N. Sevilmis, D. Weber, D. Gorecky, C. Stahl, M. Loskyll, and F. Michel. 2012. "Enabling Virtual Assembly Training in and beyond the Automotive Industry." 18th International Conference on Virtual Systems and Multimedia (VSMM), Milan, September 2–5, 347–352.

VDI 4499. 2008. *VDI-Guideline Digital Factory: Fundamentals*. Düsseldorf: Verein Deutscher Ingenieure.

Zhang, D., and J. F. Nunamaker. 2003. "Powering E-Learning in the New Millennium: An Overview of E-Learning and Enabling Technology." *Information Systems Frontiers* 5 (2): 207–218. doi:10.1023/A:1022609809036.