The Didactical Design of Virtual Reality Based Learning Environments for Maintenance Technicians

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Abstract. The paper at hand describes the necessity of developing didactically designed Virtual Reality (VR) based learning environments. Changing industrial processes triggered by the fourth industrial revolution will influence working and learning conditions. VR based learning environments have the potential to improve the understanding of complex machine behavior. The paper describes possibilities for the investigation and documentation of expert knowledge as a crucial source for developing VR scenarios. The consideration of learning objectives and the current state of the learners know how are essential for designing an effective learning environment. The basic theoretical approaches of didactics and their application to virtual learning environments will be presented with an example for the maintenance of a high voltage circuit breaker. Finally experiences from the practical use will be reflected and next steps on the way to a user specific learning environment will be discussed.

Keywords: Virtual Reality, Maintenance, Expert knowledge, learning theory, learning objectives.

1 Motivation

German industry is on the threshold of the fourth industrial revolution, also called "Industry 4.0". It is driven by the increasing integration of internet technologies with traditional industries such as manufacturing. That will lead to a more and more autonomous production process.

The core of the revolution is the complete penetration of the industry, its products and its services with software while products and services are connected via the internet and other networks. This change leads to new products and services that change the life and work of all people. [1]

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[1] Under the direction of Prof. Dr.-Ing. habil. Prof. E. h. Dr. h. c. mult. Michael Schenk.

R. Shumaker and S. Lackey (Eds.): VAMR 2014, Part II, LNCS 8526, pp. 27–38, 2014.

The technological changes are accompanied by the demographic development. [2] Experienced expert workers will retire while there are not enough well qualified young people. The challenge of companies is the integration of the experiential knowledge with the latest knowledge and information of the young professionals. A main part of experiential knowledge is tacit knowledge [3], which means that people are not aware of their experience and have difficulty verbalizing it. The first section of the paper at hand will give a short overview of how this knowledge can be investigated.

Changing industrial processes will also change the maintenance process. Maintenance technicians will take a responsible role within production with the objective of minimizing downtimes of the machine and by planning procedures under the aspect of resource and energy efficiency.

The vocational training of maintenance technicians involves facing the challenge that many machines are not available for training, cannot be used because of dangerous processes or are hardly comprehensible. Other challenges arise due to insufficient visibility of important assembly groups or the increase of invisible network processes. The understanding of processes and the resulting confidence is a prerequisite for safe and efficient maintenance procedures. [4]

Technology based learning environments that are based on virtual 3D models can overcome the restrictions of today's learning methods. For planning and arranging technology based learning environments in a target-oriented way, didactical designs are essential. Didactics describes a system of conditions and interdependent decisions which demonstrate all factors of teaching and learning in a target-oriented practice. In this context didactics refers to the following criteria: identification of learning objectives, the content of learning, application of methods, media and the pedagogical field and where teaching and learning is situated. All points interdepend and have to be considered in the respective context. [5-6]

The paper at hand will describe the conceptual design of such a learning environment under the aspect of didactics. The above mentioned didactical aspects and their application to the learning environment will be presented. An example of the maintenance of a high voltage circuit breaker serves as a descriptive example.

2 The Role of Expert Knowledge for Maintenance Processes

There are many tasks in the production process that cannot solely be taught in classroom trainings as these tasks are very complex and require the ability of decision making. This kind of problem solving competence can only be gained within the working process and goes along with experiential knowledge. In the maintenance process you will find comparatively easy tasks that follow a defined checklist and don't require special know how. On the other hand there are very complex tasks, e.g. the failure analysis and the ability of reflecting and comparing the current situation with similar experiences in the work life. [7]

"A main part of this experiential knowledge is the so called tacit knowledge. Technicians are often not aware of this special knowledge what becomes noticeable when they can't verbalize their knowledge. So, tacit knowledge is more than just the systematically received knowledge within vocational education, it is the result of the workers technical handling in their everyday work life. [8-9]" [10]

For the design of VR based learning environments it is therefore relevant to take experiential knowledge into account and to offer technicians opportunities to make experiences in the virtual world.

The challenge of bringing experiences to VR is to investigate the tacit knowledge as it is related to persons and situations. Narrative methods have revealed the potential to receive valuable knowledge from experts by telling stories. One method that is applied by the authors is the so called triad interview [11].

"It is characterized by a locally and timely defined dialogue about an agreed topic where three persons with very specific roles take part:

- The narrator as the technical expert for the topic is responsible for the validity of the knowledge.
- The listener as the novice technician who wants to learn from the expert is responsible for the usefulness of the knowledge.
- The technical layperson who is the methodical expert and moderator and who is responsible for the comprehensibility. " [10]

So far triad interviews were documented in texts which are not optimal for its application within the organization due to the limited connectivity of novice technicians to written texts. Virtual Reality has the potential to keep the narrative structure of stories and is therefore very well suited to transfer experiential knowledge whereby allowing an easy access for novice users.

3 Theoretical Basis for Learning in Virtual Worlds

We already emphasized the importance of making tacit knowledge of experts explicit and to make use of the potential of VR for its documentation. In this section we start by identifying basic learning theories for a suitable didactic design of virtual learning environments. Learning environments should provide certainty of action, especially in dangerous situations and activities which require a high level of competence. If a proper prototype does not yet exist, a qualification is already possible in the process of developing.

VR based learning environments can be classified to Leontjevs activity theory [12]. Following this theory from 1977, knowledge of employees is not only represented in their heads, but also in their working activities. In 1987 Engeström [13] extended this theory with aspects of learning and development processes. It results in the so called activity system (Fig. 1) which contains the subject (e.g. the acting technician), the object (e.g. a maintenance task) and the integration to a community of practice (e.g. a group of experts for the maintenance of a special device). Furthermore it is embedded to an organization with its rules and values that influence the handling and decision making of employees. All parameters of the activity system influence the outcome.

The quality of the outcome can be improved by assigning a well-designed didactical learning setting that is represented in the triangle of subject, object and mediating artifacts.

The paper at hand focuses on this triangle of the activity system, describes basic didactic theories from vocational education and puts them in relation to learning theories with respect to their application in VR based learning environments.

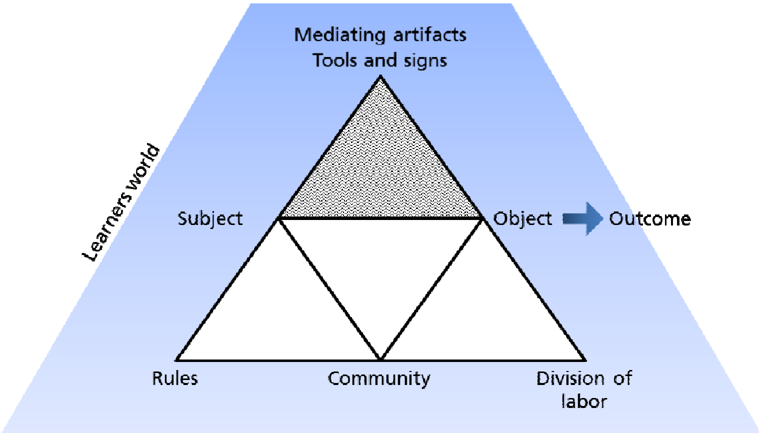

Fig. 1. "Activity- and learning theory" according to Engeström 1987 [13]

Based on the current state of the learner's knowledge, the learning objectives are defined. Therefore the following aspects have to be taken into account: learner, types of knowledge, learning objectives, the learning content and organizational structures within the company.

3.1 The Learner in the Context of a Community

According to Dreyfus and Dreyfus [14] becoming an expert in a domain is highly dependent upon a developmental progression from novice to advanced beginner to expertise.

The authors identify "(…) five stages of competence development and the four corresponding developmental learning areas". (They) "have a hypothetical function for the identification of thresholds and stages in the development of occupational competence and identity" [15]. Though, they also have a didactic function in the development of work-related and structurally oriented vocational courses.

When considering a person whose skills are developing from deficient to competent Lave and Wenger [16] state that the quality of their learning situation becomes crucial to the learning outcome. [15]. The authors point out that learning as a path from inability to ability is accomplished as a process of integration into the community of practice of those who already demonstrate expertise. [15]

3.2 Knowledge Types

There are many different terminologies to differentiate between types of knowledge. Anderson et al. [17] identify in their taxonomy of learning outcomes four major categories of knowledge relevant across all disciplines:

1. Factual knowledge,
2. Conceptual knowledge,
3. Procedural knowledge and
4. Metacognitive knowledge.

Factual knowledge consists of the basic elements. It includes knowledge of specific facts and terminology (bits of information). Conceptual knowledge refers to more general concepts and is based on the interrelation of basic elements within a larger structure that enable them to function together. It includes knowledge of categories, principles and models. [17]

Both, factual and conceptual knowledge constitute knowledge of “what”. The two other types – procedural and metacognitive knowledge – constitute knowledge of "how to" [18]. Procedural knowledge ranges from completing routine exercises to solve new problems and includes methods of enquiring information, knowing procedures and criteria for using skills, algorithms, techniques and methods. Metacognitive knowledge implies “knowledge of cognition in general as well as awareness and knowledge of one’s own cognition" [17]. It includes knowledge of general strategies, that might be used for different tasks, within diverse conditions, and the knowledge of the extent to which the strategies are effective [19]. From Anderson's [17] perspective all these types of knowledge play complementary roles in processes of problem solving. A further definition in this context is the work process knowledge. It describes a type of knowledge that guides practical work and, as contextualized knowledge, goes far beyond non-contextual theoretical knowledge. [cf. Eraut et al., 1998 at [15]] A characteristic of practical work process knowledge is the mastery of unpredictable work tasks, fundamentally incomplete knowledge (knowledge gap) in relation to non-transparent, non-deterministic work situations. This is a special feature of vocational work. Meta-competence can be created, namely the ability to cope with the knowledge gap while solving unpredictable tasks and problems in vocational work [15].

3.3 Learning Objectives

A learning objective describes intended behavior as well as special knowledge, skills and attitudes of the learner, which are caused by educational activities. The newly developed behavior has to be observable and verifiable. Learning objectives refer to three domains: cognitive (knowledge), affective (attitude or self) and psychomotoric (skills).

In 1956 Benjamin Bloom created the taxonomy of learning domains, a classification system for learning objectives in order to promote higher forms of thinking in education. The cognitive domain includes knowledge and the development of intellectual abilities. [20]

Bloom`s taxonomy involves six major categories, which are demonstrated in the following illustration, ranging from the simplest behavior to the most complex one:

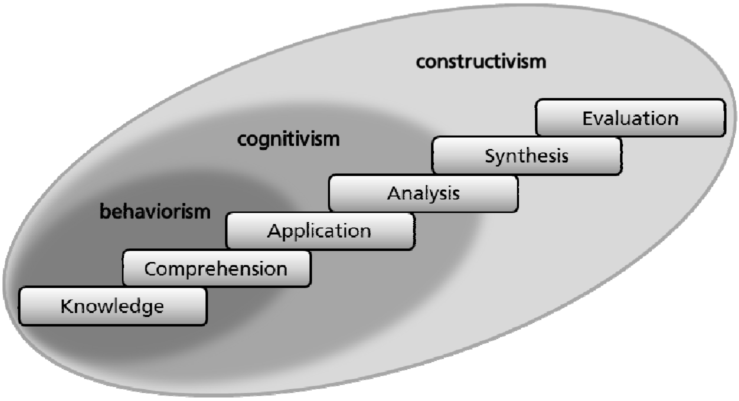

Fig. 2. Allocation of Blooms learning taxonomy to the main learning theories

The application of the learning taxonomy itself does not ensure the didactical implementation. First of all it describes the cognitive process of gaining knowledge. Together with the existing knowledge about learning theories and the analysis of learning environments the taxonomy is essential for a professional didactical design of technology based learning environments. [21] The following section describes the characteristics of the learning theories behaviorism, cognitivism and constructivism and their relation to Blooms taxonomy.

Behaviorism. Behaviorist-oriented forms of learning are suitable for simple learning processes that trigger a stimulus-response connection, which leads to permanent change in behavior. [22] This learning theory can be assigned to the lower levels of Blooms learning taxonomy, e.g. for learning facts or hand grips.

Table 1. Behaviorism – Pros and Restrictions

Behaviorism	
Pro	Restrictions
This approach is suitable only for the trigger associations for simple forms of learning. (e.g. learning vocabulary, factual knowledge)	Situations that require a lot of knowledge and are complex cannot be conveyed with this approach.
Example: Facts about the technical equipment (e.g. facts, parameters, …)	

Cognitivism. The cognitive approach focuses on the mental processing of information to knowledge. Every learning process is an active construction of knowledge.

The interaction between external information supply and the mental processes of recognition requires the learner to incorporate prior knowledge with new one. [23]

Table 2. Cognitivism – Pros and Restrictions

Cognitivism	
Pro	Restrictions
This approach is suitable for integrating information in a goal-oriented process in order to develop cognitive maps. Learning content can be adjusted automatically to the user's skills. (e.g. model learning, training videos, …).	This approach gives no ability to reflect or proof the learning context and it doesn´t consider the social aspect of learning
Example: Visualization of best-practice solutions for a maintenance task.	

Constructivism. Constructivism is an epistemology founded on the assumption that, by reflecting our experiences, we construct an individual understanding of the world we live in. Each of us generates own "rules" and "mental models," which are used to make sense of ones experiences." In essence, a constructive learning environment provides real-world or problem-based learning situations that are focused on authentic learning [24]. The theory of situated learning is a partial aspect of constructivism; it claims that every idea and human action is a generalization, adapted to the ongoing environment. From this perspective learning situations are characterized by complex, multi-perspective and problem-containing requirements.

Table 3. Constructivism – Pros and Restrictions

Constructivism	
Pro	Restrictions
VR reveals the potential for the implementation of 'learning by doing' due to its interactive characteristic. This allows users to make experiences in a safe environment, independently from the availability of the real machine.	The application needs to be designed carefully with respect of the user's level of knowledge: the high degree of freedom might be challenging for novice users as they can feel lost in the application. In this case user-specific assistance is required.
Example: Interactive exploration of the virtual learning environment including the functionality and components of the technical device.	

4 Example: Maintenance Training for a High Voltage Circuit Breaker

The following section describes a learning application that was developed for the maintenance of a high voltage circuit breaker [25]. Using the learning environment, technicians shall be prepared for acting safely and confidently in their future working environment. In this regard being able to internalize how to handle dangerous and complex processes is essential. This knowledge forms the basis for safe handling in the real working environment. [7]

Consequently the first learning module deals with the *exploration of the high voltage circuit breaker* and its two main components: three pole columns and the operating mechanism.

So far 2D-drawings (e.g. exploded view drawings) were widely used within technical trainings and are well known from user manuals. Assigning the assembly parts and their denomination using these drawings is a behavioristic learning strategy that might be suitable for easy assembly structures. In case of the operating mechanism that contains many single parts, the use of a 2D-drawing (Fig. 3a) is limited because it shows only one predefined perspective and exactly one state of the device. For the transfer to other states of the operating mechanism a higher capability of abstraction is required.

The virtual learning environment introduces a constructivist approach that connects the well-known 2D drawing with an interactive model (Fig. 3b) of the operating mechanism. Users can explore the device individually according to their demands. Used in classroom training, the mechanical behavior is no longer only presented in a teacher-centered approach. Users can now explore the components and the functionality by interactively using the virtual model on a laptop or an immersive VR system. It can be summarized that factual knowledge can be designed in a behavioristic manner in case of comparatively easy models (e.g. easy assignment tasks). For more complex systems it is recommended to extend the approach to a constructive one.

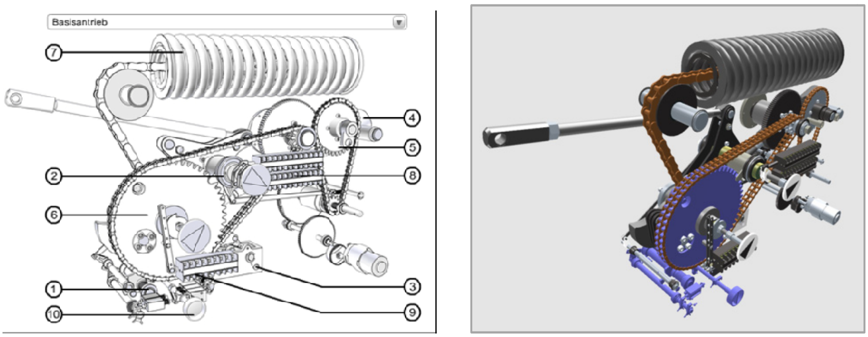

Fig. 3. (a) 2D drawing and (b) virtual model of the operating mechanism

In the second learning module technicians can make themselves familiar with best-practice solutions of chosen maintenance tasks. The visualized tasks were chosen because of their relevance and their complexity. Together with the technical experts the working processes were discussed, whereas it could be recognized that the discussion that is accompanied by a visual tool is much more intensive than just talking about a process. Before using VR based environments the work process was explained by using written manuals, checklists and videos. The use of a video is a mainly cognitivistic approach where the learner observes another person handling a situation and transfers the knowledge gained to their own task. In many situations videos are well suited, e.g. to have it available on mobile devices and to remember single working steps.

For more complex tasks a feedback from the system and the opportunity of interacting and getting further information is necessary. In the virtual learning environment a work step is described by a set of predefined animations and actions that were developed together with the technical experts, enhanced by additional information that can be accessed from the virtual scene or from a checklist. This design is following a constructive approach.

Fig. 4. Best practice solution combining animations, a checklist and different media

The learning modules are suitable for learning groups of different levels of expertise. For the learning application presented, the taxonomy of Bloom can be interpreted as follows:

1. *Knowledge:* The learner can assign the parts and assembly groups of the pole column and the operating mechanism of one type of high voltage circuit breaker, knows how SF_6 – the isolating gas within the pole column – behaves in case of compression and in which order working steps have to be executed.
2. *Comprehension:* The learner explains the functional processes of the operating mechanism, the pole column and the coupling between as well as the changes of gas and electricity during runtime.
3. *Application:* The learner can apply the knowledge to other types of high voltage circuit breakers.

4. *Analysis:* The learner can divide a real task into subtasks and can use his/her knowledge for problem-solving. Factual knowledge and process knowledge are used for understanding, analyzing and solving the problem.
5. *Synthesis:* Learners can solve problems that were not part of their qualification. Because of their knowledge and experience they can recognize relations and develop new solutions.
6. *Evaluation:* The learner has a far-reaching overview from technical as well as from the economical point of view. This gives him the ability to distinguish between different solutions following the companies' interests. The learner is also able to transfer his/her knowledge to colleagues in a suitable manner.

5 Experiences From Practical Use

"In order to evaluate the VR learning application a quasi-experimental pretest-posttest-follow-up control group design was chosen, with a group of trainees being taught traditionally by a trainer as the control group (TT) and a second equally sized group of trainees using the virtual reality application as the experimental group (VR). Hence, the trainees were assigned randomly to two groups of 10 persons each. In each training session participated 5 trainees and each one took 8 hours of work. This applies for both conditions, the TT training and VR training as well." [10] The evaluation has revealed a very high acceptance of the learning environment among users. The acceptance was rated even higher from the more experienced workers as they could imagine situations in which the use of the virtual environment would have had improved their understanding of processes and therefore their performance in the job.

The learning environment was easy-to-use for the whole peer group although it was recognized that the learning environment should be defined with respect to the user group. The design as well as the presentation of the content needs to be adapted for older users, e.g. by referring to experiences they made in their work life before.

6 Summary and Outlook

The paper at hand has presented the necessity of considering basic approaches of the didactical design when developing VR based learning environments. Based on the activity theory of Engeström the outcome of the learning system can be influenced by considering the learner, the learning object as well as media that is used for learning. Due to the technical domain that is focused in this paper, especially the field of maintenance, Virtual Reality reveals a high potential for designing learning applications as it allows the very clear and understandable visualization of complex technical processes. Learning in the real working environment is often limited because the equipment is not available or the handling is very dangerous. Learning in VR therefore contains no risk. Beside this the use of Virtual Reality allows learners to interactively solve learning tasks under the aspect of situated learning and the constructive approach of learning.

Future work will focus on the visualization of experiential knowledge. As experiential knowledge is mainly tacit knowledge, narrative methods for its investigation, as described in the paper at hand, need to be developed and applied. They can be improved by using VR-based applications that allow the documentation of stories already within the interview process and can keep the narrative structure. This ensures a better transfer process. Furthermore the access and the presentation of knowledge will be designed adaptively by means of the user characteristics (age, pre-existing knowledge).

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