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Towards VR-based systems for school experiments

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Abstract

In this paper we present the steps towards a well-designed concept of a VR system for school experiments in scientific domains like physics, biology and chemistry. The steps include the analysis of system requirements in general, the analysis of school experiments and the analysis of input and output devices demands. Based on the results of these steps we show a taxonomy of school experiments and provide a comparison between several currently available devices which can be used for building such a system. We also compare the advantages and shortcomings of VR and AR systems in general to show why, in our opinion, VR systems are better suited for school-use.

Keywords: VR-based systems; Edutainment; School experiments; Interaction devices;

1. Introduction

Appropriately teaching children knowledge about our world, the universe and complex processes of life is a challenging task, because many scientific processes and their correlations span multiple layers, some of them impossible to perceive with basic human senses. In order to visualize these processes, some kind of approximated models and descriptions are used. On top of that an observer should possess the ability of abstract thinking in order to understand this transferred knowledge. The necessity of being able to think this way is usually just what makes it difficult for children to master science. At this point the utilization of novel

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technologies like AR or VR could be helpful. Nowadays, AR and VR-systems are important because of their potential to make work easier, complex things better understandable and engineering and experimentation costs lower. They have already found their place in many different domains like medicine, automotive industry, mechanical engineering and pilot training. Usage of these technologies at schools can change the learning process in a positive way because they will make it possible for teachers to visualize the theoretical models more clearly and also allow students/pupils to experiment with these models in different ways, thereby making them more understandable. They may have a positive impact on education quality [1-4].

However, the design of AR and VR-based systems for school experiments is still a big challenge because of factors such as cost, usability, robustness, healthiness and maintainability. All these factors must be considered not only during the device selection phase but also during the implementation of interaction techniques and the whole software system. It is also important that the system supports a wide range of experiments from different scientific areas to make it worth the investment.

In this work we concentrate on the design process of a system for the accomplishment of virtual, scientific school experiments. We analyze school characteristics and demands to define the system requirements and then propose a configuration for a system, which might be attractive for education institutes.

The paper is structured as follows: Section 2 contains information about related work. In section 3 a taxonomy of school experiments is presented from the developer's point of view. In section 4 the steps are proposed that need to be done during the system design. It also includes the analysis of the current state and consequential requirements the system must fulfill. In section 5 the example implementation of the system is presented. Finally, section 6 summarizes the main statements made in this paper.

2. Related work

During the last decade numerous efforts were made to put VR/AR systems into a school context for educational purposes. In this section we provide a brief overview of some of these projects.

The "Cyber-Classroom" [5] is a commercial product that was developed by the Company VISENSO. It is an interactive system focused on school application, making use of current VR technologies. Starting at several thousand Euro, the main disadvantage of this system is its price. Also, the system is only aimed for group use and cannot be used as a single place system.

Another project is "Science Center To Go" [6] which was started in 2010 in the context of the "Lifelong Learning" program. In the scope of the project a set of miniature exhibits was developed. Each exhibit represents some kind of virtual experiment from a particular scientific area. AR technologies were utilized in the project for visualization and interaction purposes. The developed exhibits are marker-based, but the markers used are similar to the real objects they represent. The system's main disadvantage is the small set of experiments it offers. Also, the object based markers result in high management and maintenance overhead. Extending the exhibits set increases the number of objects, therefore also increasing the overhead further on.

In the project "Mathematics and geometry education with collaborative augmented reality" [7] an interactive AR system for learning the concepts of mathematics and geometry was realized. The software offers numerous functions for construction and manipulation of geometric primitives. In total three hardware configurations are supported: The Augmented reality classroom, Projection Screen Classroom and Distributed Hybrid Classroom. The project provides a good platform for further work, but due to utilization of expensive input and output devices it is not really applicable in schools.

Surely there are a number of other projects with the same aim. The mentioned projects however present the three common directions developers usually take during the design of interactive systems for schools: pure VR, pure AR and mixed. They also show that the implementation of such a system is theoretically and practically possible. However, the main problem still is the price. Trying to get around that problem and make the system more affordable for schools, the developer designs it in such way that it can be used by many students simultaneously (one student acts and the rest observes), shifting the purpose of the system towards the direction of presentation.

3. Classification of school experiments

Before starting the system design one should understand the nature of the experiment itself. Experimenting means systematically and specifically manipulating some substance and/or observing its behavior in order to prove or disprove a predefined hypothesis that is based on previous observations and/or manipulations. School experiments are often of a simplified form, so the procedure and results are also understandable for non-experts.

Fig. 1. Taxonomy of school experiments

In this section we provide some classifications of typical school experiments (cf. figure 1). The classification should result in a better understanding of which experiments can be transferred to an AR/VR context and which overvalue could be gained due to this transfer. As a base for this section a set of books [8-13] for teachers was taken. The books contain a number of experiments for schools with descriptions of procedures and expected results.

The first classification is based on the body characteristics of the objects the students observe, interact with and manipulate during the experiment. It shows that, in general, we can divide the mentioned objects into three categories: rigid body (e.g. wooden spheres), flexible and disembodied objects (e.g. sound or forces). It is also possible to subdivide flexible objects into shapeless objects (e.g. liquids or gases), and shape-maintained objects (e.g. spiral spring). Based on this classification the first conclusions come to light. E.g., it becomes clear that the experiments with rigid body objects are easy to transfer one-by-one into VR because of the objects' simple description and their relatively simple physics. The assumption is also confirmed by the fact that a high number of developed systems for experimentation are limited to the cases where only rigid bodies are used. The experiments with disembodied objects are also easy to reproduce; since those objects are usually replaced with rigid bodies (e.g. one uses arrows to represent the forces). On the other hand the experiments with shapeless objects are more troubleshooting, because of complex simulations, which nowadays can be accomplished only using high-end hardware.

Another classification takes into account the size of the objects one experiments with on the one hand and the fact that human visual perception and manipulation abilities are limited on the other hand. Here, the experiments may be subdivided into four groups: macro-layer experiments, micro-layer experiments, human-layer experiments and mixed-layers experiments.

Macro-layer experiments are usually limited to observation because of the objects' huge size, like orbs, so humans cannot really manipulate them or change their properties. Often one could accomplish those experiments only by using special devices (e.g. telescope). Due to the lack of manipulation possibilities macro-layer experiments are usually very time consuming. The reproduction of such experiments in a VE might be very useful, because the possibility to operate and to modify objects can be provided. Due to this the time needed for experiments may be also decreased significantly.

Micro-layer experiments imply the manipulation and observation of tiny-sized objects that cannot be seen with the naked eye. Special devices like microscopes are used to accomplish this kind of experiments. Using VR systems to recreate micro-layer experiments, the teacher will be able to shape them more clearly, livelier and understandable for students. Usually they are also easily transferable to VR, because of the simple constitution of the micro-objects.

The human-layer experiments collate the experiments where the pupils can observe and manipulate the objects without any particular devices. The results of the experiments are seen with the naked eye or made visible using some devices. Imitation of such experiments in VE, gives the possibility to visualize the disembodied objects which are part of the experiment. Displaying additional information will also contribute to better understanding of the processes occurring during the experiment. The replacement of the real objects with virtual objects will reduce the costs of the experiment.

A high amount of mixed-layer experiments could be found in chemistry. During the accomplishment of these one usually blends different substances on the human-layer and can often see the result with the naked eye. But to understand how the substances react with each other one should observe the processes that occur on the micro-layer.

Another way to distinguish school experiments is to take into account factors like time and safety. Considering the time factor one can group the experiments to those which could be immediately executed and those which require a large amount of time. The latter encompass the processes which could not be affected by humans or could be affected slightly only, like for example the growth of plants. Taking into account the safety factor we can say that there are experiments which are safe for pupils and experiments which are dangerous under certain circumstances. For example experiments with radiation are dangerous. Taking into consideration the time and safety factors, it is clear that the transfer of the dangerous and/or time consuming experiments into virtual environments is advantageous by allowing students to execute experiments faster and without risk.

The state of the art software development process based on modularization therefore allows for building of an extensible and robust system. One can classify the experiments considering the scientific topics they belong to. This kind of classification allows to define software blocks which collate experiments with the same theoretical background. In order similar objects with similar physics are used in such experiments.

The last classification brings together the experiments by reference of sense(s) one should use to understand the outcomes. The five traditional senses humans possess are the sense of hearing, olfaction, the gustatory sense, the tactile sense and vision. Some experiments address multiple senses simultaneously. This taxonomy shows that only experiments which address the vision and hearing senses can be put in a VE context in their entirety. The reproduction of the experiments based on touch sense is only possible with expensive devices, while the implementation of the experiments based on smell and taste senses will be even more problematical.

4. Designing a system

In this section we provide the steps needed during the system design. An overview of the entire design process with resulting outcomes is presented in figure 2.

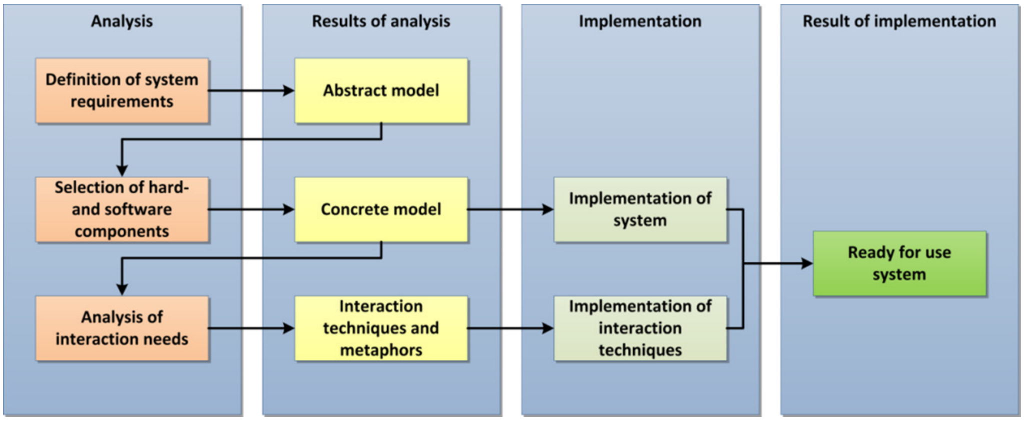

Fig. 2. Design process and outcomes

Following [14] we first want to analyze the three aspects which are important for the system design. These are: target groups, usage-context and activities the system will allow to do. The analysis of the mentioned aspects yields the possibility to determine the system requirements that define the abstract model of the system. Based on these requirements it is possible to choose the proper hardware components that will define the concrete model of the system. Knowing the hardware components and application specifics of the system the developer becomes able to select the appropriate interaction techniques and metaphors.

4.1. Target groups

The target groups of the system are teachers and pupils. **Teachers** are well skilled persons who are familiar with current technologies like cell phones, computer and television. They probably are not familiar with innovative technologies like tracking systems. Therefore, they cannot maintain and configure such complex systems. **Pupils** are children from 10 to 18 years old. They are also familiar with current, but not innovative technologies. In this age they are often careless so they could sometimes handle expensive devices improvidently. They also can have some permanent or temporary health disabilities. They could be left- or right-handed. Some of them have no stereoscopic perception. Based on these assumptions the system requirements presented in the table 1 must be set.

Table 1. System requirements based on analysis of target groups.

Point of view	System requirements
Teacher	easy to maintain and configure; software must not crash
Pupil	easy to use; robust; allow to interact with left and right hand; allow to switch between 3D and 2D mode; allow to interact in standing and sitting position

4.2. Context

The system will be used in the context of biology, physics and chemistry classes of middle or high schools. For schools, the following assumption is typical: Schools do not have a high budget and do not have too much space where the system could be installed. The following statements are made for the classes:

- 20 to 30 pupils participate in a class
- Teamwork is claimed and promoted
- One class unit takes 45 minutes
- Experiments do not take place frequently

The above-mentioned statements resulting in the system requirements are presented in table 2.

Table 2. System requirements based on analysis of context.

Point of view	System requirements
School	low-cost (many units of the system are required); worth the investment (support of wide range of the experiments and application possibilities); compact
Lesson	up to 2 pupils can work together; small training period; interaction with the system must not disturb other pupils

4.3. Activities

The main activity one can use the system for is accomplishment of the virtual scientific experiments. For that purpose the system must provide at least one input device, one output device and one powerful enough computer unit. The software component that contains a number of implemented experiments and provides a well-designed graphical user interface in order to manipulate the experiments is also of great importance. Taking into account the fact that the experiments do not take place frequently, the system must be reusable.

Another activity the system must provide is the creation of new virtual experiments or adoption of the existing experiments to particular topics of science classes. In order to allow this some kind of authoring tool should come up as part of the system’s software component.

Taking into consideration the mentioned activities one can add further system requirements: **Reusability** and **Extensibility**. These two factors are of great importance for many products, but especially for school specific systems. Bear in mind the reusability requirement during the design process will lead to a system that is worth the investment for schools. Fulfilling the extensibility requirement will lead to a community where the teachers and scientists can share new scenarios and objects for experiments resulting in an increased life span of the system.

4.4. Specifying the system

The system requirements defined in the previous section make it possible to decide which properties the final system should match. In this paper we want to distinguish between two possible types of systems: a VR and an AR system. The term augmented reality implies in this case both augmented and mixed reality. Therefore, AR is defined as a system that operates with the objects presented in the real world. It tracks their position and orientation and displays additional information depending on that data. The objects may be of arbitrary shape. Consequently, the system must possess a database with object descriptions in order to be able to recognize those objects in the real world. Often the abstract representation (markers) of the objects instead of the real objects is used in order to simplify the tracking routine. Considering these properties the following statements can be made:

- The scientific experiments involve a high amount of objects. For an AR system this means that all those objects must be presented in their physical form.
- The software's complexity and the complexity of the system itself will increase if real objects are used. This is the case because the objects will be part of the system. The high complexity will result in higher cost. The large amount of the real objects will also increase the administrative workload for teachers.
- The replacement of the real objects by markers can be confusing, because the markers do not describe the objects in their entirety. The marker could be easily lost, because of their typically small size.
- The visual report of additional information based on simulation of the real life processes must be perfectly synchronized with the actions performed by pupils.
- The use of real objects ensures proper haptic feedback and the addressing of the olfactory sense (e.g. by chemistry experiments).
- Head-mounted output devices, which are often utilized as part of an AR system, are often fragile, uncomfortable and expensive.
- Extending the experiment set will require, in some cases, adding new objects.

VR systems, in contrast to AR systems, only work with virtual objects. Taking the properties of VR systems into consideration with the purpose of the system for virtual experiments the following statements are made:

- The VR system does not have to track the objects. It knows at any time where the objects are and which properties they possess. Therefore, the software component of the system is less complex.
- Creation, storage and management of the objects cause no cost.
- The number of virtual experiments is easy to expand by adding some new software modules.
- The properties of the objects can be easily adjusted by the user.
- The simulation is always synchronized with user actions.
- The simulation of any arbitrary environment is possible.
- The accomplishment of the dangerous experiments can be executed without any health risk.
- Haptic feedback is possible, but only rudimentarily. The smell sense can't be addressed without great effort.

Regarding the above made statements we propose to choose a VR system as basis for the system for virtual school experiments. To go further into the specification we suggest to prefer non-immersive VR system (aka Desktop VR) to immersive one, because of its low price and compactness. As an output device for a non-immersive VR system a common 3D display may be chosen. Those are, nowadays, ease of access and low priced. Some input devices with their characteristics are listed in the section 4.5. Using any of them one is able to complete the hardware design of the targeted system. Handling in such way it is easy to realize an inexpensive system. The school will also be able to use the system for other purposes that are different from accomplishment of scientific experiments. Therefore, the system will be more attractive for schools' budgets.

4.5. Input devices

In this section we provide a short overview of input in low-price segment that were already used with success in a number of different scientific projects and are suitable for accomplishment of virtual school experiments. The choice of the input device will have a high impact on the types of possible interaction techniques. Table 3 can be used for scoring of the input devices, therefore, making it possible to select the appropriate device for the system.

Table 3. Comparison of the input devices

Characteristics	**Wiimote**	**Kinect**	**Falcon**	**SpaceNavigator**
Price	from 40€	from 100€	249$	from 100€
Robustness	Average	High	High	Average
Additional maintenance effort	Replacement of energy source	No	No	No
Calibration	Easy	Easy	Easy	Easy
Two-handed interaction	No	Yes	No	No
Multi-user (one device)	No	Yes	No	No
Input sources	visual digital buttons	visual audio	digital buttons movable grip	digital buttons pressure-sensitive handle
Compactness	High	High	Average	High
Haptic feedback	Rudimentarily	No	Advanced	Rudimentarily
Native DOFs	4	3	3	6
Positional data	Relative	Relative	Absolute	Relative
Min. distance to user	60 cm	40 cm	-	-
Precision	Average	Average	High	Average
Cordless	Yes	No	No	No
Additional requirements	Yes - infrared bar	No	No	No
Suitable for both hands	Yes	Yes	Yes	Yes
Additional costs	Yes - energy sources	No	No	No

5. Example implementation

Based on the knowledge presented in the above sections we have built an example system for the accomplishment of virtual school experiments. The following hardware components were utilized: a common medium-class PC, two Novint Falcons as input devices (one for each hand) and a simple 3D capable display as an output device. We selected the mentioned input device because of its low price, high robustness and intuitive operation. The haptic feedback the device can simulate is also an interesting feature, which can be utilized in many different experiments. Using two such devices within one system, we can ensure the simultaneous work of two students at one workstation or provide two-handed interaction for one student.

For the demo purpose the application *MagSim* was used which was implemented within the scope of the EXAR project [15] by using the *basho* VR framework [16]. The aim of this application is to simulate and visualize the three-dimensional magnetic fields of two magnets that are manipulated by the user. In its original state the application was used together with a video see-through head-mounted display. The HMD was also equipped with a tracking system that determines the position and orientation of the magnets the user operated. Using information from the tracking system, the magnetic field lines were simulated and blended with the real world image recorded by the HMD’s cameras. Despite the positive feedback from the participants in the evaluation of the system students and teachers, we recognize that this system won’t find its way in school because of the high price of its hardware components and the narrow applicability.

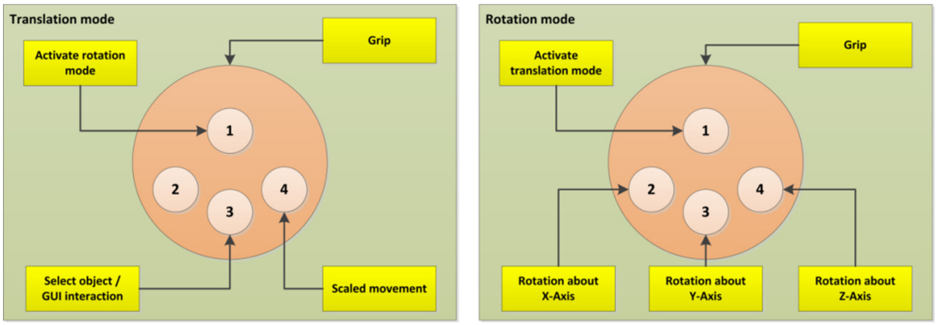

Fig. 3. Application controls: (left) translation mode; (right) rotation mode

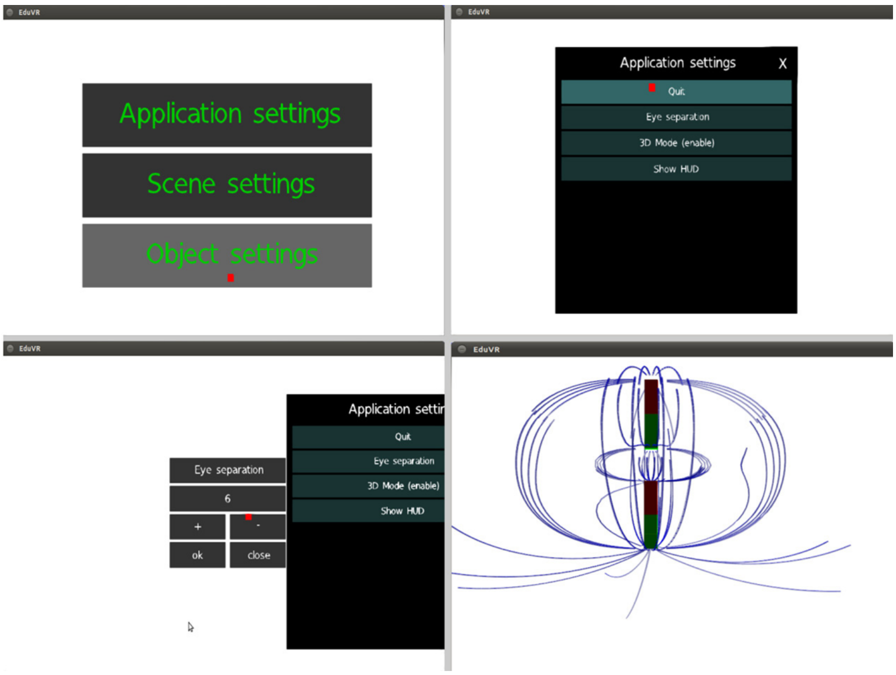

Fig. 4. Application views: (top-left) main menu; (top-right) application settings menu; (bottom-left) widget for manipulation of numeric values; (bottom-right) scene view

In this work we ported the application to Desktop-VR so it became usable with the system described above. It was also expanded by a freely configurable graphical user interface. The concept of the GUI was designed with respect to the specifics of the system and with high degree of generalization. Due to this it can be used with any type of virtual school experiment. It implements three types of menus: application settings, scene/experiment settings and context menu for the currently selected object. The Head-up-Display is used to visualize the state of some parameters that are meaningful for the running experiment. Finally, a set of widgets can be used to manipulate some numeric parameters of the experiment, e.g. strength of the magnetic field. Application controls via the Novint Falcon and screenshots of the application are shown in figures 3 and 4.

6. Conclusion

In this paper we have discussed the steps need for design of interactive VR system for accomplishment of virtual, scientific school experiments. We have presented the classification of the mentioned experiments from the developer point of view, which shows on the one hand which overvalue comes up due to reproducing of the experiments in VE and which experiments it is possible to transfer using currently available technologies on the other hand. The school demands were analyzed and the system requirements become clear due to that. We have shown that it is not enough to design a good usable system, but also such factors as robustness, extensibility and reusability are of high importance especially for schools. The advantages and disadvantages of the VR and AR systems were discussed referring to targeted system resulting in a statement that VR systems are more suitable for that kind of work. By discussing related work it was shown that many developers tend to create systems that focus more on visualization than interaction (one system for all) rather to create a low-cost system so that all students could work simultaneously at their work station (one system, max. two students). We have proposed to utilize the hardware the schools already have, like computers, and only extend this by needed devices, like low-cost input devices, presented in section 4.5. Such an update can follow stepwise depending on the current budget of the schools. By using commodity 3D displays instead of the specific and expensive output devices a high degree of reusability of the system can be achieved. At last we want to emphasize, how it is important to build up a base for community platform, since it is the only way for software to expansion with minimal cost.

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