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Possibilities and Determinants of Using Low-Cost Devices in Virtual Education Applications

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ABSTRACT
Virtual reality (VR) may be used as an innovative educational tool. However, in order to fully exploit its potential, it is essential to achieve the effect of immersion. To more completely submerge the user in a virtual environment, it is necessary to ensure that the user's actions are directly translated into the image generated by the application, which can be achieved by means of various devices, such as tracking systems and VR headsets, as well as haptic devices. Recently, VR has become the focus of e-entertainment, which has resulted in the appearance on the market of numerous, low-cost peripheral devices. The paper discusses the examples of potential applications and steps necessary to adapt low-cost devices to immersive educational applications.
Keywords: virtual reality, low – cost devices, Virtual learning environments

INTRODUCTION

Education enthusiastically turns to state-of-the-art achievements of computer engineering. Virtual environments promote creation of learning conditions that involve pupils and students in solving complex problems (Garris & Cantoia, 2012) and in directly experiencing physical properties of objects such as shape and size (Antonietti et. al., 2000), which can be achieved by means of haptic devices (Grajewski et al., 2013).

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State of the literature

- Virtual and haptic technologies are increasingly used as decision-making support systems and immersive educational simulations.
- A trained person can explore a virtual environment, for example for educational and exercise purposes in medicine, for exploration of dangerous workplace conditions, or for e-commerce (gaming).
- A major limitation for the development of immersive haptic training applications has been the cost of peripheral devices enabling interaction with the virtual environment.

Contribution of this paper to the literature

- The use of low-cost VR systems (tracking systems, head-mounted devices and gesture-recognition systems) combined with rapid prototyping technology that is widely available to the average user, for the purpose of creating immersive training simulations.
- Demonstration of potential problems and possible limitations associated with the preparation of immersive training workplaces.
- Examples of practical applications of virtual and haptic technologies in immersive educational simulations created by the authors.

One such dynamically developing area is simulation systems. A simulation as a training tool is more and more commonly used in, for example, training medical students and students in related subjects. A simulation makes it possible for trainees to acquire essential skills prior to first contact with patients, which is of particular importance in surgery. In this area, VR simulators may not only supplement, but may even replace traditional teaching methods. In the virtual world, it is possible to simulate certain procedures, such as palpation examination, injections, and laparoscopic procedures (Ullrich 2010) without endangering a patient's health or life.

Modern IT tools permit generation of VR environments of high complexity, in terms of both logical and graphical aspects. Thus, VR systems enable users to interact in real time with elements of an artificially created 3D world (Scherman & Craig, 2003). However, to ensure faithful reflection of reality, it is necessary to involve a user's many senses, not only vision. It is possible to achieve a state of profound submergence described as immersion (Romano & Brna, 2001) by means of appropriate combination of a variety of VR devices, such as automatic positioning and orientation systems, with pre-programmed virtual worlds. In the process of using VR simulation as a tool in training, in which a trainee's involvement is of great importance, this sensation of immersion is vitally important.

The use of immersive training applications is particularly justified when training may threaten a trainees' health or even life, or when training executed under normal circumstances is particularly time and money consuming (Okraniec et al., 2009).

To ensure a more complete user immersion in VR, it is essential to directly translate a user's actions onto the image generated and displayed by the application. There are numerous methods to achieve this effect. One such method is extension of interaction between trainees and the virtual environment by introducing so-called virtual teachers, who provide feedback on actions carried out by trainees (Johnson & Rickel, 1997). Other methods involve user motion tracking systems (Welch & Foxlin, 2002).

Until recently, an important limitation in the development of civilian immersion applications was the cost of peripheral devices that enabled interaction with a virtual environment. This was true for professional HMD type devices and tracking systems, as well as haptic devices. However, companies involved in e-entertainment, communication and visualization showed interest in them, and that, along with popularization of 3D printing, resulted in a considerable lowering of costs. Thus, VR technology is becoming widely and practically available.

Popularization of rapid prototyping technology, as well as common use of low-cost devices in this industry, has enabled introduction of entity objects, indispensable in simulations, into virtual environments in a relatively cost-effective way. Such devices may be tools, steering panels, USG probes (Buń et al., 2015) etc. Therefore, in many situations, it is unnecessary to use haptic devices in order to simulate objects that are to be manipulated by the trainee. Availability of devices such as OculusRift of Samsung Gear VR, with built-in tracking of a user's head (Hamrol et al., 2015) disposes of the need to buy any additional tracking systems, or permits purchase of a less expensive device. This opens new opportunities for designers of training applications and immersive systems, and at the same time poses many new challenges in terms of selecting and adapting equipment for particular educational applications (Hamrol et al., 2015).

This paper discusses examples of applications of low-cost devices to build immersive training systems and points out their typical problems and limitations.

EXAMPLES OF LOW-COST VR EQUIPMENT

Low-cost tracking systems

Many tracking systems are available with varying working parameters and, more importantly, at varying prices. Tracking systems may be divided according to their mode of operation:

- Mechanical tracking systems – they use sensors arranged in a kinematic structure (Zhaoliang et al., 2011). In this category, we can also include accelerometers and gyroscopes. In these devices, angular measurement is vital and may be executed by means of a variety of transducers, e.g. potentiometric transducers, optical, magnetic or capacitive encoders or resolvers.

- Acoustic tracking systems – a mode of operation of acoustic systems is based on detection of sound waves. Here we can include the Intersense IS-900 positional tracker. All commercially available acoustic systems emit ultrasound impulses that determine position of an object by means of a known wave propagation velocity in a selected medium. This occurs by calculating the time necessary for a wave to travel from an object being tracked to the sensor. Sensors are usually fixed in definite points in the measurement space and an ultrasound wave emitter is located on the object being tracked (Welch & Foxlin, 2002).
- Electromagnetic tracking systems – they measure a local vector of an electromagnetic field by means of a magnetometer or current induced in an electromagnetic coil passing through windings while the magnetic field is reversed. Three magnetic sensors perpendicular to one another and located in one casing may be used to generate a 3D vector displaying sensor orientation against a field emitter. It is also possible to make use of the magnetic field generated by Earth or to use an active source of magnetic field consisting of multiple coils. Magnetic induction in individual coils in a strictly defined sequence enables determination of position and orientation of the object being tracked against the source (Welch & Foxlin, 2002). Ferromagnetic materials and conductors in the surroundings may affect the shape of the magnetic field. Eddy currents induced by changing magnetic field may lead to incorrect readings of position and orientation of the object. This problem may be eliminated by removing elements that disturb functioning of the system. The Polhemus LIBERTY is an example of a magnetic tracking system that enables tracking objects that have six degrees of freedom. It consists of a transducer, four receptors connected to it and an active source of magnetic field (marker). A disadvantage of this system is the previously mentioned high susceptibility to disturbances caused by metal objects present in the working environment and by the necessity of installing on the object being tracked markers of much greater mass and dimensions than in optical tracking systems.
- Optical tracking systems – markers used in them typically facilitate determination of position of the object or direct tracking of the object/user with more complicated algorithms. An example in the category of marker-less systems is the device Kinect, manufactured by Microsoft. It uses visible light, registered by a regular camera, as well as infrared light emitted by the device and reflected from the object being tracked. Here, a digital camera detects a user's silhouette and an infrared detector assists in assessing its distance from the device. Optical systems tracking objects by means of light emitted by a single diode or reflected by a marker can track only the position of the object and not its inclination against an accepted coordinate system. When two or more markers or objects that emit light radiation by themselves are used, it is necessary to ensure their stable position throughout the entire simulation. Thus, it is possible to track both linear movements along all axes, as well as rotations of the objects around each axis.
- Hybrid tracking systems – they combine the systems discussed above.

Designers of immersive systems, where user movement tracking is necessary, have to define requirements set before devices to be used in such a system. The selection of a suitable tracking system may appear a daunting task due to the multitude of devices available on the market because work parameters of a given tracking system decide the extent of immersion, and thus the success of implementation. A search for a suitable solution starts with an in-depth analysis of a planned immersive application. It is common that the choice made relies on a multitude of criteria. Each criterion may be expressed as parameters to characterize user movement tracking systems, and are as follows:

- Tracking accuracy (mm, deg) – defines tolerance margins of position and orientation tracking of object in space
- Workspace (m3) – partially determines the area in which it is possible to track objects; in applications, not only absolute cubic capacity, but the shape of available space must also be taken into account
- Latency (ms) – information that characterizes the length of time between an appearance of a given state in reality and an appearance of a corresponding event in the application
- Number of objects tracked
- Methods of communicating with an application – defines the method of data transfer and of communicating with external programs
- Obtained data – defines the format in which data are shared or sent to simulation

A comparison of sample parameters of low-cost tracking systems can be found in **Table 1.**

Table 1. Selected parameters of tracking systems

Evaluation criteria	Tracking system PS-Tech PST-55	Microsoft Kinect	Optitrack V120:Duo
Tracking accuracy	<1mm, <1 deg	<3mm	0.5 mm
Workspace	16.17m^3	8m^3	27m^3
Latency	18 ms	90 – 102 ms	8.33ms
Number of simultaneously tracked objects	up to 15 (independently)	2 (skeletal systems)	1
Communication interface	VRPN, tracked, DTrack emulation, CSV export, SDK	SDK	SDK
Obtained data	position (x, y, z), orientation (head, pitch, roll), Euclidean matrix of transformation	position of selected human body parts	position (x, y, z) and orientation
Price	$3,000.00	$200.00	$2,299.00

In light of an abundance of market offers and a number of parameters that must be taken into account in selecting a tracking system, it is recommended that a multi-criteria analysis should be carried out along with any decision-making algorithms, e.g. Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and fuzzy logic.

Low-cost HMD

Currently, the e-entertainment industry, as well as the general public, focus on low-cost HMD devices. The dynamics of development of such devices is best illustrated by comparison of two devices built with Oculus VR form – OculusRift DK1 and Samsung Gear VR Innovation (S6), which appeared on the market two years apart from each other. Although these two devices do not have a built-in system for tracking the movement of a user's head in space, they do enable tracking orientation. A significant difference between low-cost devices and professional HMDs is the fact that the former have only one screen, whereas in most professional devices there are two independent screens acting as supplementary monitors.

OculusRift DK1 was launched on the market in 2013. The device is characterized by a relatively high field of vision (one of the biggest available in any type of HMDs) and by quite low weight. Its shortcomings are limited screen resolution and the fact that the only method of focusing the picture relies on replacing the lenses supplied by the manufacturer. This may be particularly awkward for users with sight defects such as myopia or far-sightedness. This precludes such users from using HMD without corrective lenses. The most important characteristics of the device are presented in **Table 2**.

Table 2. Selected parameters of the OculusRift DK1 (Oculus 2013)

Product specification	
Platform	PC
Display class	7" 1280x800 60 Hz LCD
Resolution	640x800 per eye
Low-persistence	No
Optics	One aspheric acrylic lens per eye (7X)
Interaxial distance	63.5 mm
Tracking	3 DOF angular
Tracking frequency	1000Hz
Tracking latency	~2ms
End-to-end latency	50-60ms
FOV	monocular : 99°H binocular : 106°H

Samsung Gear VR is a more recent product, developed by Samsung in collaboration with Oculus VR. In this device, a Samsung Galaxy S6 (Head-on with Samsung's Gear VR 2015) smartphone acts as the display, providing the necessary computing power and also access to the software shop. The role of Gear VR is to hold the smartphone on the user's head and to direct the picture to the user's eyes by means of specially set lenses. The lenses are designed for pupillary distance between 55 and 71 mm. Users frequently complain about the difficulty of adjusting focus, although it is possible to adjust screen location. In certain sections of the application the image is blurred, regardless of varying regulation settings. It sometimes happens that even though the sight ahead is clear, objects on the sides are blurred. Parameters of the device are presented in **Table 3**.

Table 3. Selected parameters of the Samsung Gear VR

Product specification	
Platform	Android
Display	5"1' 2560x1440 60 Hz LCD
Resolution	1280x1440 per eye
Low-persistence	No
Optics	One aspheric acrylic lens per eye (7X)
Interaxial distance	55 ~ 71 mm
Tracking	3 DOF angular
Tracking latency	<20ms
End-to-end latency	50-60ms
FOV	96°H
Sensors	Accelerator, Gyrometer, Geomagnetic, Proximity

A rear camera on the smartphone is uncovered, thus it is potentially possible to use the goggles in augmented reality applications. However, by default, Gear VR only enables the user to determine a distance to the nearest obstacle without removing the device. An inbuilt touchpad provides limited communication with the virtual environment, but it is rather awkward for the user during simulations.

Consumer versions of both OculusRift and Gear VR, with improved parameters, are scheduled to launch on the market in the coming months. Also, other manufacturers, so far absent from the VR industry, such as HTC and Sony, are planning to launch their HMD devices. Their products are presented in **Figure 1**. Since these devices are designed for e-entertainment purposes, additional programming work will have to be carried out in order to adapt them for educational applications relying on interpretation of signals from inbuilt receptors and image transfer, or possibly image deformation. Manufacturers of software for VR applications are trying to deal with these problems and in new versions will try to include tools that will assist in deforming the image without specialist knowledge and without any additional IT tools.

a) b)

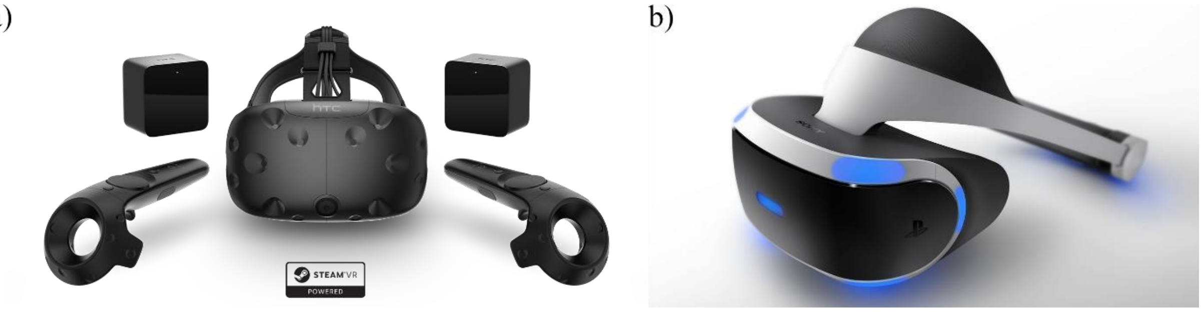

Figure 1. a) HTC VIVE (HTC 2013), b) Sony PlayStation VR (PlayStation VR 2016)

Gesture recognizing and pointing devices

Among low-cost devices that can enhance the level of immersion, devices that recognize a user's gestures as well as pointing devices can be listed. Here, we can include a Myo device, which can read muscle tone in a user's arm by means of electromyography (EMG).

It is possible to recognize five gestures based on the data from sensors in the Myo device. The gestures can be ascribed directly to keys on the keyboard or to the movements of the mouse. Unprocessed EMG data may be obtained by means of the Software Development Kit (SDK) function, which makes it possible to undertake a higher number of actions based on scripts in the LUA language. This device enables tracking (to a limited extent) of the movements of the hand. Specifications of the device can be found in **Table 4**. A considerable shortcoming of the device is the fact that each time it is placed on the arm, it must be calibrated, which may take up to five minutes. During that time, the Myo device tries to create a stable electrical connection with the forearm muscles, where if not successful, may result in failed recognition of certain gestures.

Table 4. Selected parameters of the Myo device (Myo 2013)

Product specification	
Platform	Windows, Android, MAC OS, IOS
Armsize	Expandable between 19 - 34 cm forearm circumference
Weight	93 grams
Thickness	1.15 cm
Sensors	Medical Grade Stainless Steel EMG sensors, Highly sensitive nine-axis IMU containing three-axis gyroscope, three-axis accelerometer, three-axis magnetometer
Procesor	ARM Cortex M4 Processor
Haptic Feedback	Short, Medium, Long Vibrations

MATERIALS AND METHODS

Case and problem definition – immersive educational VR applications

In the course of designing immersive applications, a question must be asked: "What is the most significant influence on immersion?" Certainly, among such factors are:

- Graphics quality – depends on the programming environment applied, available data (3D models, texture graphics, etc).
- Simulation logic – the scenario is determined by the part signaling the need for a given application, but must be verified by the team that creates the VR application.
- Operational fluency – first and foremost it depends most on graphics quality (workload on the graphics card, or processor) and on checking instructions working in the background (scripts responsible for simulation 'logic'). Additionally, operational fluency may be affected by considerable delay in data transfer from peripheral devices, e.g. tracking systems.
- User's imagination – a factor which is entirely beyond a programmer's control.
- Movement mapping – depends on the equipment selected and data from tracking systems.

It must be emphasized that designers of applications and VR systems do not have much say in some of these areas.

The use of low-cost devices enables construction of training applications in a wide array of subjects. Below, examples of immersive training systems will be discussed in which low-cost devices have been successfully used.

Simulation of medical ultrasound examination

The details of functioning and construction of simulations have been described in (Buń et al., 2015). The application was built for the training of medical students based on a 3D anatomic atlas (Hamrol et al., 2013). In order to develop user reflexes necessary to correctly conduct a USG examination, an optical system to track the position of an ultrasound probe was used. The optical tracking system PST-55 was selected because it enables tracking of objects in the range of 40 centimeters to several meters. It makes use of retroactive markers to facilitate determination of object position. On every object that must be recognized by the system, a definite and unique arrangement of markers is deposited, and then entered into the device memory. For a USG simulation system, a standard USG probe was modified using incremental techniques. Additionally, removable elements were introduced beyond the gripping section of the probe. A modified probe, along with supplementary elements, is shown in **Figure 2**.

Figure 2. a) Prototype of a USG probe, b) Test system (Buń et. al 2015)

After a prototype of an immersive system was built, the influence of additional removable elements on object recognition by the tracking system was studied. It was observed that they increased the ability of the tracking system to recognize objects, especially when the user covered a more sizable portion of the gripping part of a USG probe with his hand. The results of the study are presented in **Figure 3**.

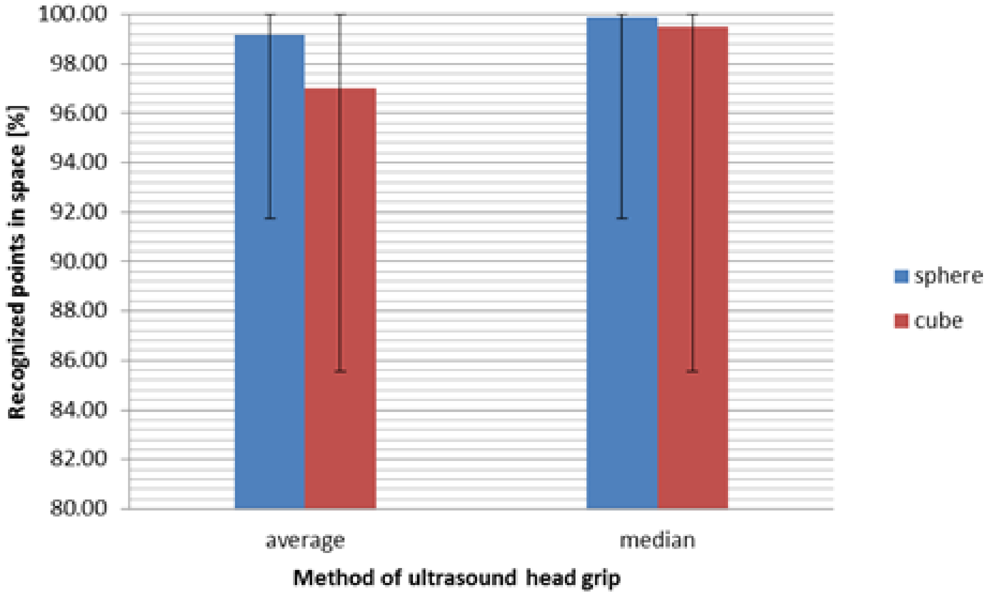

Figure 3. Percentage of recognized points of the whole test procedure (Hamrol et al. 2015)

Based on the results, the authors found that optical tracking systems with passive markers can be successfully used in immersive applications. A prerequisite here, however, is a correct location of markers, which may involve the necessity to introduce geometric changes into objects to be tracked.

Integrated immersive and haptic virtual workplace for manual assembly

Within the scope of work undertaken, the authors studied a possibility of using a low-cost haptic delta-type robot to build an immersive training application (Grajewski et al., 2015). The immersion effect is achieved by combining HMD, tracking system and haptic technologies. Initially, the principal task of the robot was to move the arm to a position in which the operator's arm could touch it in order to simulate an encounter with an object in VR space. The authors added a special algorithm of positioning the end-effector of the delta robot against the tracked object, i.e. a user's hand. In order to simulate the operation of manual assembly, it was decided to modify the end-effector by adding a small DC motor with a gearshift, as well as an encoder, in order to simulate real resistance that may be sensed by the user while turning a screw into the cylinder block of the motor (**Figure 4**c).

Figure 4. (a) Delta robot, (b) robot's end effector representing the surface of the virtual object, (c) immersive and haptic simulation of the manual assembly (Grajewski et al. 2015)

Initial results of studies performed on a test group show that the application prepared in this way, involving a haptic device with a force feedback effect, may be successfully used in the teaching of simple assembly operations.

The use of immersive VR application in the training of production employees – ongoing research

Currently, the application is in the development stage. An immersive training situation is being constructed that uses low-cost devices to train production workers. In a manufacturing company such as glassworks, specialist training to operate and maintain a glass molding machine takes approximately six months. Throughout the training period on an operating production line, an increase is observed in the number of defective products, duration of die exchange and injury risk among workers. Training conducted on a specially prepared work-stand equals increased cost, as a section of the production line is closed. Therefore, training in VR seems to be the perfect solution, as it is unnecessary to close any sections of the production line and the company does not incur any losses due to defective products.

The application is ready to work in desktop as well as in immersive mode. In desktop mode, the application may be launched on any laptop computer with a Nvidia card that has been manufactured in the past five years. In immersive mode, the application uses low-cost devices such as OculusRift DK1 or Samsung Gear VR, the Kinect tracking system and the Myo gesture recognition system. The need to generate two images and to track the position of a user's hands and orientation of his head forces an increase in computing power of both CPU and GPU. Both HMD devices use algorithms created by Oculus VR.

This application is designed to assist in the training of glass molding machine operators. A complete program of training includes both operation of a steering panel on the production line and support activities such as exchange of a tube that directs molten glass into a mold. The scenario for the application lists several stages and modes of work. Upon starting the application, the trainee has to define a mode of work – whether it is a demonstration, training, test, or a complete course covering all the stages listed. In each stage the trainee will be informed about obligatory activities by a virtual trainer, or by a graphic highlighting the elements that must be selected. Feedback on execution of tasks or errors made may be provided by a virtual operator or in visual messages.

After completing programming work a study on efficiency of the application is planned. The test will be carried out in three groups. The first group will be trained by a virtual trainer, the second will complete a course in which information about compulsory steps and mistakes made will be given only by means of visual messages. A control group will be made up of glassworks workers. Prior to the test, the third group will have an opportunity to familiarize themselves with the virtual environment. Throughout the test, a length of time will be measured after which the duration of tasks and number of mistakes will no longer improve.

Participants will be asked to perform all the tasks. No feedback will be provided on correct or erroneous execution of a given procedure. If a serious mistake is made, it will lead to a collision between the elements of the machine being operated.

A control group will also have a possibility to give a more detailed evaluation in writing describing any problems in the application or the devices.

CONCLUSION

As e-entertainment grows dynamically, which is connected with development of new peripheral devices as well as with lowering their cost, it is possible to create cost-effective training systems that ensure a level of immersion in VR that is sufficient to develop specific indispensable reflex actions in a controlled environment. However, in order to fully exploit the potential of low-cost devices, it is essential to undertake additional programming work. This work will include developing an interface for data transfer between application and equipment, but also offsetting low parameters of the equipment.

Examples quoted in this paper demonstrate that it is possible to create immersive systems and educational applications that make use of cheaper versions of professional equipment. However, a complete evaluation of efficiency of such solutions will be possible only after long-term studies.

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