MECHANICAL DESIGN LEARNING ENVIRONMENTS BASED ON VIRTUAL REALITY TECHNOLOGIES

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ABSTRACT

This study explores the potentialities of Virtual Reality for improving the learning process of mechanical design principles. It is focused on the definition of a proper experimental VR-based set-up whose performances match functional design, assembly design and geometrical tolerances prescription learning purposes. Benchmarking of VR technologies is based on the analysis of perception and on the usability and presence provided by the assessed systems. An experimental plan is defined and evaluation metrics are set.

Keywords: Mechanical Design, Virtual Reality, Experience-based Learning Environment

1 INTRODUCTION

Virtual Reality (VR) technologies provide novel modes of human-computer interaction that can support the learning of mechanical and industrial design subjects. Instead of simple desktop-based systems, they stimulate not only the sense of vision, by providing stereoscopic image views and complex spatial effects, but also the senses of touch, hearing and motion by respectively adopting special haptic, sound and motion devices.

The present work aims to explore the potentialities of VR for mechanical design teaching. The observation of the students difficulties to interpret 2D drawings for identifying the impact of geometric and dimensional tolerances chains into design solutions, detecting functional and assembly errors, evaluating the proper manufacturing operations to produce an artefact force instructors to seek for innovative technologies able to improve students perception. Research into the use of VR has indicated that they may improve the learning process creating an augmented environment for the 3D virtual models tests cases investigation and description. The vast amount of available VR technologies makes difficult the identification of the best system to improve mechanical design learning. The scope of our research is the experimentation of VR in mechanical design and the objective evaluation of the limits and advantages of available technologies. The present paper is makes progress against the achievement of this research task. It aims to define both a proper VR set-up for mechanical design and an experimental protocol for the following validation tests. A method for benchmarking available VR technologies is proposed. It is based on the study of design lessons by traditional means of representation, on the identification of the main critical activities where paper-based tools and CAD systems fail and on the correlation between the identified activities and the VR technologies usability, provided presence and depth of sensations that users perceive during the exploration of the experienced-base learning environment.

2 BACKGROUND: VR IMPROVES MECHANICAL DESIGN LEARNING

The concept of experienced-based learning has been widely explored in design education. It consists of the following steps: concrete experience of the design problems and solutions, observation of the achieved results and formulation of abstract concepts and generalizations [1]. Other research claims that learning without execution of action remains at the state of mental action and therefore remain distant from real action [2].

These preliminary considerations point out the importance of adopting educational methods and tools that allow students to experience the topics of design lessons not only by 2D representations that make difficult design solutions interpretation and errors detection. On the other side, visualization of 3D models support learning and teaching but perception is limited only to sight and do not significantly increment learning. The use of real specific laboratories may overcome the above-mentioned problems, making students experienced of mechanical equipments and manufacturing operations.

Design education can be performed by two main different approaches [3]:

- face-to-face education that improves the interaction between learners and learners and learners and instructors. The main problems in experience-based learning application are related to the difficulty to retrieve information, develop collaborative work and experience design solutions in real time;
- distance education that implies learners and instructors in geographically separated sites. Three different approaches and related communication media are proposed: a) one-way instruction by mail, radio and television, b) single technology instruction by computer-based or web-based learning, and c) blended learning that combined face-to-face with asynchronous and/or synchronous computer technology.

We state that face-to-face is more successful than distance learning in mechanical design where the understanding of the design principles requires a concrete experimentation of general principles.

Most of recent studies on face-to-face design education highlight the potentialities of computer aided design tools and of VR technologies for improving perception in education and training applications [4], [5]. The main recognized advantages are:

- they improve the spatial ability of learners as they allow not only the visualization of 3D models but also their experimentation. Furthermore students find them much easier to understand things from diagrams or models simply looking at graphs or mathematical algorithms;
- they provide a link between education and practice first because they provide access to sophisticated laboratory facilities without the high costs generally associated with the up keep of them and secondly because they are more and more used in real industrial design processes. Therefore they are training tools to prepare students for job;
- they facilitate knowledge sharing and collaboration in multidisciplinary teamwork;
- they allow to achieve a sense of presence instead of traditional visualization technologies and to interact with virtual models in a very intuitive and natural manner;
- they stimulate motivation and contribute to the sense of fulfilment in students.

Although the above-mentioned advantages, no definite experimental results have been achieved and there is no much information available on their application. This is due mainly to the high costs of VR technology implementation and to the difficulty to identify the proper VR technologies combination for the specific learning tasks.

3 THE VR-BASED SET-UP FOR MECHANICAL DESING PRINCIPLES LEARNING

3.1 VR technologies classification based on perception

Perception in design education plays a crucial role in incrementing knowledge. Although several researchers concentrate on visual perception [6], it is worth to notice that individuals perceive objects and the space surrounding them also by all other sensorial modalities.

Human beings depend on five senses to experience their surroundings and infer from the physical objects and environment around them. Users interact with objects and their interfaces, by experiencing them with the sensorial modalities that generate a set of stimuli that once elaborated at a cognitive level are transformed into actions. In order to obtain similar conditions by VR, it is necessary to identify which technology better stimulates each sense and provides deep sensations in the users.

The proposed classification starts from the Burdea definition of VR as “a high-end user-computer interface that involves real time simulation and interactions through multiple sensorial channels” [7]. Available VR technologies are divided into four classes (visual, sound, haptic and motion) that correspond to the four sensorial channels involved in the virtual experience (vision, hear, touch and motion). Each of them provides the corresponding sensorial feedback to the users.

All these technologies are also combined with the computing hardware for VR simulation and real time interaction support, and with the software toolkits to map the input/output devices with the simulation scene, model 3D objects and create object libraries for optimizing VR simulations.

Only if the VR technologies are combined they provide a deep involvement of all senses. Simulating the reality of design experiments, the VR-based environments allow students to real experience the product design and perform specified tasks

3.2 A method for VR technologies benchmarking for education purposes

In order to improve experimental-based learning by VR technologies students should feel being involved in the virtual environment and be allowed to test principles by touching, smelling, hearing and moving the objects they are working with. It has been demonstrated that the communication medium influences the form of interaction and knowledge perception and cognition, particularly when learners are unfamiliar with the communication technologies used to deliver instruction and perform design tasks [10]. Therefore we state that in VR applications for educational purposes, it is important to evaluate not only presence to improve perception but also systems usability.

Based on these considerations, the benchmarking of VR technologies combination is based on three different classes of heuristics: usability, presence and depth of sensations. Usability concerns the capacity of the VR interfaces to accommodate to the users needs. The degree of the system’s usability depends on different characteristics such as barrier free, ease-to-use, intuitiveness, etc. Presence means “being immersed” and refers to an emotional and mental state of being involved in the virtual scene. It denotes the level of engagement. The sense of presence is determined by some characteristics of the system such as interactivity, collaboration, non-constraining, navigation support, etc. Finally, the depth of sensation refers to the degree of the sensory feedback (both visual, tactile, auditory) that users feel while exploring the

virtual scene. In order to manage the complexity of all possible combinations of VR technologies, we introduce two 3D matrices. The first allows the management of the combination between haptic, visual and navigation technologies; while the second matches the first achieved combination with sound technologies and assigns a value for each final combination to each heuristics in order to assess the systems performance (figure 1, step 1).
In order to identify which VR combination is suited to teach specific mechanical design subjects we introduce an additional matrix that correlates the activities necessary to perform experienced-based learning and the levels of sensory feedback necessary for perception and cognition (figure 1, step 2). While the first matrices are fulfilled by VR experts as they relate to the technical and functional performances of the analysed systems and are not design learning-oriented, the second should be fulfilled by professors of mechanical design for their deep experience of learning environments.

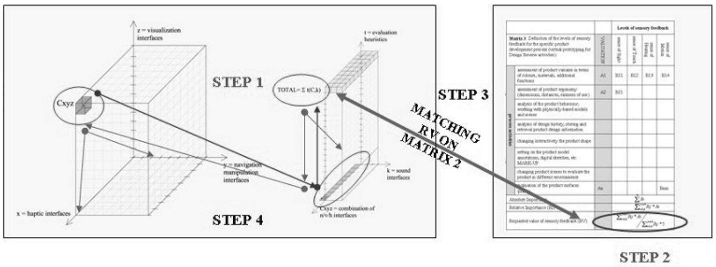

Figure 1 Synthesis of the proposed method

The achieved level of the second matrix is matched with the heuristics value assigned to the different combinations and the proper VR system is identified (figure 1, steps 3 and 4). An exhaustive description of the proposed method can be found in a previous research work where it was applied for identifying the VR system that better answers to design reviews activities requirements [8].
The above-described method is used to identify the proper VR technologies combination for improving different stages of mechanical design learning, instead of traditional 2D representations (sketches, drawings, images, photos) and 3D models showed by Computer-Aided Design (CAD) systems. The first step in the method application concerns the analysis of which activities should be performed to achieve a good understanding of lesson’s subjects. Two different mechanical design topics have been explored and for each of them the necessary teaching activities have been traced:

- Functional design principles and assembly mechanisms aim to develop a critical attitude in the students that should be able to interpret mechanical components and assemblies, detect functional errors and identify assembly or manufacturing problems. In functional design, the instructor shows different functional design alternatives in order to clarify concepts. Examples are necessary to improve understanding.
- Dimensional and geometric tolerances aim to develop the ability of identifying assembly and manufacturing problems in different design solutions and which tolerances guarantee the final product quality. In particular students should be able to verify the consequences of drawing determined tolerances chains on the manufacturing process and to identify the proper references for geometrical and dimensional tolerances.

Professors in mechanical design have been involved in the definition of the levels of sensory feedback to perform each activity. The evaluation values represent the importance that each activity represents for the learning process and for improving traditional 2D and 3D representation means.
Three different VR technologies combinations have been chosen for the assessment that respectively point out single-user learning environment, the haptic feedback to augment tactile perception of materials and components interaction and image complexity to improve the visual perception of design solutions in a collaborative environment (fig 2).

			Levels of sensory feedback			
Definition of the levels of sensory feedback for teaching **functional design principles and assembly mechanisms**		VALUATION	sense of Sight	sense of Touch	sense of Hearing	sense of Motion
Activities to improve the learning of functional design and assembly principles	assessment of design solution alternatives by combining different standard components with similar functions	5	5	1		3
	Assessment of the impact of design decisions on manufacturing and assembly operations	5	3	5		3
	Identification of manufacturing and assembly problems by analyzing manufacturing operations and equipments	2	5		1	
	Identification of the right functional design solution by analyzing the manufacturing and assembly cycle costs of different alternatives	3	4		1	1
	Detection of functional and assembly errors in different design solutions	5	5	5		5
	Understanding components interaction in assemblies and identification of the proper sequence of assembly operations	3	5	5		5
Absolute Importance (∑bij)		61				
Relative Importance (∑ai*bij)		253				
Requested value of sensory feedback (∑ai*bij/ ∑5*bij)		**0,87**				

			Levels of sensory feedback			
Definition of the levels of sensory feedback for teaching **dimensional and geometric tolerances**		VALUATION	sense of Sight	sense of Touch	sense of Hearing	sense of Motion
Activities to improve the learning of dimensional and geometric tolerances	Interpretation of a design solution and identification of the tolerances	3	5			2
	Identification of the dimensional and geometric tolerances references and of the difference between them	3	5	2		4
	Understanding of the differences between tolerances according to the control techniques	4	3			3
	Identification of the manufacturing and assembly problems deriving from wrong tolerances chain	5	5	1		3
	Assessment of the impact of tolerances chain on the assembly operations	5	5	1		5
Absolute Importance (∑bij)		44				
Relative Importance (∑ai*bij)		188				
Requested value of sensory feedback (∑ai*bij/ ∑5*bij)		**0,7**				

Figure 2 Assessment of the sensory feedback necessary to improve the learning of functional design and assembly principles and dimensional and geometric tolerances

The application of the method highlights the best solution for each mechanical design subject (figure 3).

Evaluation heuristics		Evaluated combinations of VR technologies		
		C1	C2	C3
usability	barrier free		5	5
	intuitiveness		5	3
	easy-to-use	1	5	3
	integration	3	4	4
	flexibility and efficiency of use	2	4	4
	clear recognition	2	4	4
	customization	3	3	3
	latency	1	2	5
presence	interactivity	3	2	5
	collaboration		4	4
	non constraining	1	3	3
	natural engagement	3	3	2
	navigation and orientation support	1	5	4
	image complexity	2	5	5
depth of sensation	realistic haptic feedback			5
	stereo imaging (immersion)	5	5	5
	image resolution	2	5	5
	viewable by multiple users		5	5
	realistic sound feedback	5		
	TOTAL	34	64	75
	RELATIVE TOTAL	**0,36**	**0,7**	**0,78**

Figure 3 Combinations C1, C2 and C3 consist respectively of HDM coupled with a common mouse, a large volume display provided with stereo imaging and an optic tracking system and a similar display with a point-based device for simulating assembly operations

The achieved values can be improved by associating the input/out devices with the software toolkit to manipulate 3D models. While manipulating 3D parametric models obtained by CAD systems can experience functional design and assembly principles, tolerances subject requires additional information related to material properties (e.g. roughness) and real time deformation of nominal models according to tolerances combinations. In this case physically-based models seem to better match mechanical design learning requirements.

3.3 The experimental protocol to test VR in mechanical design education

In order to verify the real applicability of the proposed method and to test the advantages connected with the use of the achieved VR technologies combinations, an experimental protocol is set. Two different groups of mechanical design students with different levels of design practice, attending respectively the first and the third year of a Mechanical Engineering Course, are submitted with two different types of exercises for each identified lesson's subject. Each type is performed both with traditional means of representation (slides, 2D drawings, 3D models visualized on desktop displays) and with the identified VR system. A list of metrics is defined to evaluate the performance of the VR systems for the specific purposes: time for detecting functional and assembly errors, number of detected errors, the quality of the interaction with the VR media and with the 3D models, time necessary to understanding general principles, etc. Recording students at work by Video Interaction Analysis techniques allow collecting data useful for the objective evaluation of the metrics.

4 CONCLUSION AND FUTURE WORK

The present work is a step forwards the exploration of the advantages of VR in experienced-learning approach application. It aims to define a proper experimental set-up for testing if mechanical design learning is incremented by immersing students in a virtual environment. Although the use of VR in teaching and learning is not new in itself, experimentation is mainly based on available technologies not really set for the specific purposes. In this context our scientific contribution consists in the selection of a VR system according to the analysis of perception and cognition mechanisms in the learning process.

REFERENCES

[1] Kolb, D.A. *Experiential Learning: Experience as the Source of Learning and Development.* (Prentice Hall, Englewood Cliffs, NJ, 1984)

[2] Oxman, R., Educating the designer thinker. *Design Studies*, 1999, 20, 105-122.

[3] So, H. and Brush, T.A. Student perception of collaborative learning, social presence and satisfaction in a blended learning environment: relationships and critical factors, *Computer & Education*, 2008, in press.

[4] **Moran, S., Rubio, R., Gallego, R., Suarez, J. And Martin, S. Proposal of interactive applications to enhance student's spatial perception,** *Computer & Education*, 2008, 50, 772-786.

[5] Towle, E., Mann, J. and Kinsy, B. Work in progress – development of tools to improve the spatial ability of engineering students. *Frontiers in Education*, 2005.

[6] Mohler, J. L. Methodology on Spatial problem Solutions Among High and Low Visual Achievers. *Journal of Industrial Technology*, 2008, 24, 1-9.

[7] Burdea, G.C. and Coiffet, P. *Virtual Reality Technology, 2th Edition*. (John Wiley & Sons Inc.Publication, USA, 2003)

[8] Mengoni, M., Germani, M., Bordegoni, M. Virtual Reality systems: a method to evaluate the applicability based on the design context", *in CD-ROM Proceedings of the International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, September, 2007.

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