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Application of Virtual Reality Techniques in Design of Ergonomic Manufacturing Workplaces

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Abstract

This paper presents possibilities of application of the immersive VR and the haptic technologies during the complex process of design and virtual prototyping of the manufacturing workplaces characterized with a high level of ergonomic quality. Two case studies are presented: a workplace for stud welding and a set of two workplaces, for hole drilling and manual assembly. In the first case study, haptic device with force feedback effect was used to improve ergonomics of main operator activities. In the second case study, immersive approach was used, namely Head-Mounted Device, tracking and gesture recognition systems, to test and improve ergonomics of the whole workplace. Application of VR techniques allows to present the virtual prototype of the workplace in its real operation environment, limiting the need for use of real mock-ups. Therefore, Virtual Reality allows to conduct a number of analyses related to designed prototypes, such as: dimensions of devices and possibilities of adjustment to height of the human operator, and arrangement of control and signaling devices according to the rules of ergonomic design. To conduct these analyses, full interaction between user and workplace must be programmed, including collision detection, kinematics of the devices and possibilities of activating their various functions in relation with other objects in the virtual scene.

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Keywords: virtual reality; haptic devices; workplace design; ergonomics;

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1. Introduction

Innovative approach to effective design of modern manufacturing workplaces requires solving problems related mostly to their complexity. Designer of such workplaces is required to be experienced in many engineering branches (basics of mechanical design, mechanical engineering, ergonomics), to obtain sufficient knowledge about problems occurring during operation of such a workplace, with special consideration of work safety.

Among a number of innovative technologies aiding the work related with construction of prototypes of manufacturing workplaces, a particular attention needs to be paid to Virtual Reality techniques. Immersive Virtual Reality, Augmented Reality and haptic technologies are the most noteworthy techniques. They allow to design and test virtual prototypes of workplaces without necessity to build physical prototypes. They also allow future operators to explore the work environment, in which the workplace will be placed.

This paper presents possibilities of application of the Virtual Reality technologies during the complex process of design and virtual prototyping of the manufacturing workplaces characterized with a high level of ergonomic quality.

2. Virtual technologies aiding the design process

Taking into consideration a wide scope of modern technologies aiding the design work related with construction of manufacturing workplaces, the particular attention needs to be paid to virtual technologies [1]: Virtual Reality systems (VR), Augmented Reality (AR) environments and haptic technologies.

2.1 Virtual Reality systems

Virtual Reality (VR) is scientifically defined as an application of the computer technology to create an effect of interactive, three-dimensional world, in which objects have spatial form. A computer-generated environment with a stereoscopic visualization is a basis for each virtual reality solution. In the virtual environment, interactive control over the presented image is really important and gives the feeling of presence and of being part of a virtual scene, not from the position of observer, but as a participant of virtual simulation. Interaction allows a user to control the virtual object and whole virtual scene in real time [2,3] .

Main criterion of division of the Virtual Reality systems is a level of immersion of user into the virtual environment. Further division can be made regarding used software and hardware. VR systems also include scientific visualization systems, which do not give user a sense of immersion.

The immersion is achieved mostly by stereoscopic projection, giving the user an illusion of spatial depth. There are several different methods of obtaining the stereoscopic image:

- Active projection with shutter glasses,
- Passive projection with polarized glasses,
- Personal projection.

The personal projection ensures the highest level of immersion. Helmets for the personal projection are named Head Mounted Displays (the “info-helmet” notion has been also proposed in the literature [4]). The HMDs work on the basis of two separate display screens, put in front of the user’s eyes. Two separate images need to be supplied to these displays, to make the user see a stereoscopic image. The feeling of immersion is achieved mostly by tracking the user’s head movements and changing the view accordingly. The user is placed inside a virtual world which surrounds him completely. The user can move freely around and all the time he sees an image from the direction he is looking in. An example of the HMD device is shown in the fig. 1.

Fig. 1. nVisor MH-60V HMD available in the Poznan University of Technology

Another solution for personal projection are the CAVE™ systems. They resemble small rooms with large screens in place of walls. Basic systems have three walls, more advanced systems also have a roof and a floor. Rear projection is used to generate the image on all active walls. The user is surrounded by three-dimensional image of surroundings and is equipped in a special glasses which help him to see the stereoscopic image. The glasses are also equipped in the position trackers, much like in the HMDs – to ensure the image changing in front of the user's eyes when he changes his position. The system requires at least three projectors to generate fully synchronized image, sometimes a cluster computing is required to make the display smooth in real time. An example of the CAVE projection is shown in the fig. 2 [5].

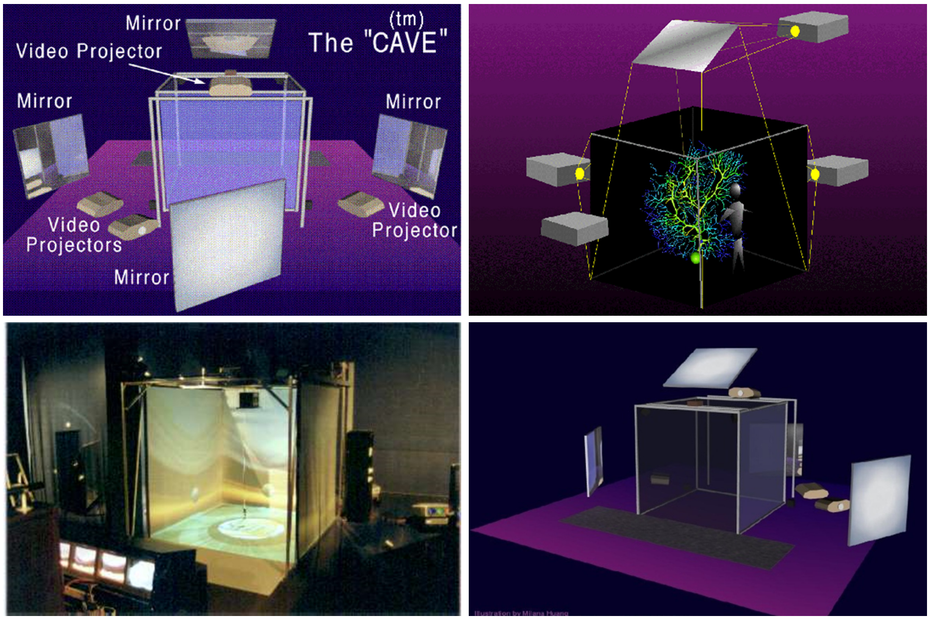

Fig. 2. CAVE™ system – principles [5]

Multi-user projection is achieved using large screens (Power Walls – fig. 3) with rear or front projection. The passive stereoscopy requires two separate images to be projected onto a screen through special filters, different for the left and the right eye. Glasses worn by users also have special filters, so the left eye receives different image than the right eye, which gives the depth effect. Passive systems require two standard projectors or one specialized, double-lens projector. The active stereoscopy is based on rapid switching between images for left and right eye. The active, shutter glasses are synchronized with the projector, so again both eyes receive a different image. The active systems have gained a significant popularity in commercial solutions (3D TVs), as the solution is generally cheap, although it is arguably more tiring for the users. The large-screen solutions allow many users to watch the stereoscopic image at once and they allow to view designed products in 1:1 scale.

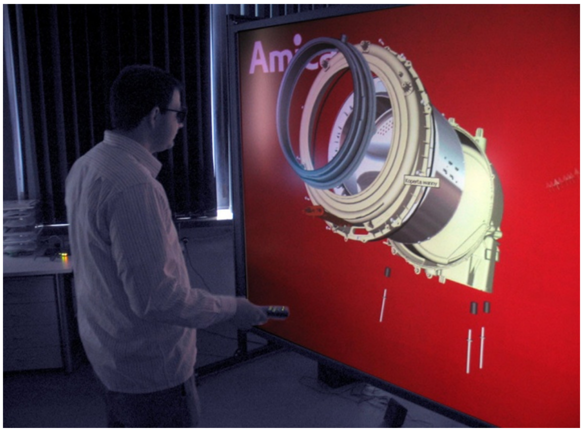

Fig. 3. Power Wall system for passive stereoscopic projection [5]

2.2 Augmented Reality systems

The Augmented Reality (AR) is a concept of blending between the computer-generated image and real world view – the interactive 3D image is superimposed on top of the regular field of view of the user, to integrate the virtual world and the real world into one [1,6]. As opposed to VR systems, in which the user is separated from the real world and immersed in the virtual world, the AR systems ensure free interaction with the real world, complement it and allow to enhance the human perception using interactive, virtual objects [1,6].

For example, design of machines and devices with AR support allows to present the design of the virtual prototype of a machine in a real environment, limiting the need for physical mock-ups. Thus, application of the AR technology allows to conduct a number of analyses related to designed machine prototypes, such as:

- Dimensions of the device – to adjust it to the height of the human operator,
- Arrangement of signaling and control devices according to rules of ergonomic design.

The user conducting an ergonomic analysis has a possibility of full interaction with the virtual device. Thanks to this, a need for time-consuming and costly computer simulations and analyses is limited somewhat [1].

2.3 Haptic technologies

Haptic technology (the Greek word *haptikos* meaning touch) allows user to interact with the computer through tactile feedback. A haptic device (phantom, glove, model, manipulator) is equipped with a number of sensors, which record parameters like direction and velocity of the movement. These parameters are processed in an appropriate way and in effect, the user is receiving feedback, for example through vibration at selected locations with appropriate amplitude and frequency [7,8].

A typical haptic system (also named a tactile system) is usually composed out of a central computer unit (hardware + software) and an external device working with the computer – usually the haptic device resembles a three or six-jointed industrial manipulator. The arm of the manipulator is designed to be operated by user and it is composed of straight segments connected by cylindrical joints (fig. 4). Joints of the manipulator are equipped with sensors that register values of the angular movement along their axes. The software then calculates the exact position (and orientation for six-jointed devices) of the manipulator end effector (held by the user during the operation) by solving the forward kinematics problem. This information is sent to the software in real-time. Usually, basing on this data, software calculates a force vector which is sent back to the device, making it react with the force feedback [9], giving the user a sense of touching a solid object. The end effector may be equipped with an additional button or a number of buttons, allowing the user to interact with the system in more than one way.

Analyzing the publications concerning application of possibilities and advantages of the haptic technologies it can be stated, that these technologies, despite being in an initial state of development, bring very promising results of applications in many disciplines (medicine, rehabilitation, aeronautics, robotics and many more).

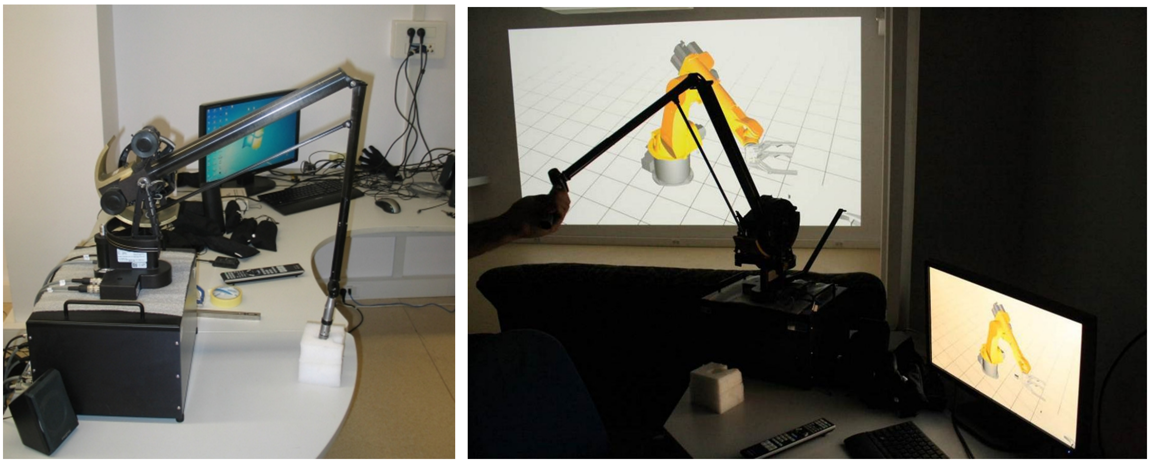

Fig. 4. The haptic manipulator – SensAble Phantom Premium 3.0/6 DOF

2.4 Virtual-aided design

Problem of aiding the design using virtual reality has been a subject of a number of scientific studies and R&D works for the last two decades. The special focus is on use of Virtual and Augmented Reality for industrial design processes.

The first registered uses of a virtual environment for industrial design were conducted at the University of North Carolina, USA. A team of architects created a virtual building, which could be thoroughly explored. The possibility to view the project "from the inside" enabled the scientists to correct the design errors even before the building was physically constructed [8,10,11]. Later research activities were related to building virtual environments containing so-called “virtual artifacts”, which could be operated or come into interaction with a user through different types of in-out devices.

Analyzing research works published so far, concerning application of possibilities of the virtual technologies in design, it can be noted that the virtual technologies are increasingly used for studies in field of work safety and ergonomics. It is caused by considerable possibilities of these technologies in that subject – it allows to expand the scope of research and it can result in significant cost reductions related to manufacturing of real workplaces, as virtual prototypes can replace physical prototypes. Examples of such applications are described in the further part of the paper.

3. Design of ergonomic workplaces using virtual technologies

3.1 Ergonomic aspect of design of manufacturing workplaces

In times of a strong competition on worldwide markets it is not enough to develop simply a „good" workplace. The designer needs to strive towards not only the best efficiency, usefulness or quality, but also ergonomics, which not so long ago was a term known only to certain specialists [12].

Ergonomics is frequently defined as an interdisciplinary subject, dealing with adjustment of devices, tools, machines, environment and work conditions to anatomical and psychophysical properties of a human being, ensuring efficient and safe work with relatively low biological cost [8,13,14,15]. Some of the definitions define ergonomics as a knowledge needed for proper design of tools, machines, working systems and environments ensuring safe and effective work [13].

One of the most important tools for ergonomics in the design work are directives and standards. The first directives have been created in the 70s of the 20th century, as an expression of integration processes in Europe. The integration created a need for common basics for integrated design. Basic international law regulations in this field are European Union directives. All member countries have introduced these directives to their own law. So far, minimal requirements of work safety and ergonomics in the following fields were developed:

- management of health and safety,
- manual weight lifting,
- work with computer monitors,
- use of personal protection,
- use of machines and tools,
- design of the workplace [15].

Environments of Augmented Reality and Virtual Reality may be effective solutions for complex analyses of developed designs of prototype workplaces, from the viewpoint of meeting the rules of ergonomics. The workplace designed in an appropriate manner allows the operator to work in the most effective way possible. Risk of injuries and stress is therefore seriously limited [1].

It still needs to be remembered to initially perform the deep analysis of problems related to design of spatial workplaces operated directly by human. During design of the “human-machine” system (manufacturing workplace is a special case of such system), taking the human factor into consideration is a must. Construction of a modern, ergonomic workplace should be optimized in a way to significantly decrease frequency of problems occurring during its use. To make the operator work comfortably, the workplace should be designed in a way to minimize a number of activities that need to be performed and limit activities that may interfere with other activities. Equipment of the manufacturing workplace should be also adjusted to anthropometric and biomechanical properties of an operator. Arrangement of important elements (tools) on the analyzed workplace is also very relevant. All necessary elements should be placed within the reach of the operator or in his field of view.

The above described guidelines should always be taken into consideration during building virtual models of manufacturing workplaces.

3.2 Assumptions regarding an effective design of spatial, ergonomic workplaces with use of virtual technologies – cognitive work

In the own studies leading to define the main assumptions and stages of design of ergonomic manufacturing workplaces, ergonomic techniques frequently used in workplace design were applied:

- Techniques based on the anthropometric databases, using dimensions of users' bodies to define the necessary workspace shape,
- Computer-aided design (CAD) software, using the digital human models (3D phantoms),
- Hybrid methods (ergonomic design using CAD systems, Virtual Reality and haptic technologies along with physical objects – prototypes)

Realized cognitive work in field of optimization of solutions for ergonomics and work safety, used during design of modern manufacturing workplaces, have led to prepare experimental research workplaces (described in the chapter 4), which were used to conduct a number of analyses and studies and realize several practical design tasks. Preparation of the experimental workplaces required to define, as mentioned before:

- assumptions regarding influence of the workplace conditions on health of the worker and efficiency of his work,
- assumptions regarding arrangement of particular elements (tools) in the workplace space,
- initial assumptions regarding the studied workplace from the viewpoint of its adjustment to anthropometric and biomechanical properties of the operator,
- guidelines regarding possible optimization of solutions for ergonomics and safety of work.

On the basis of conducted analyses and observations, a set of guidelines regarding optimization of design and manufacturing solutions of the studied workplace was prepared. The guidelines were prepared taking workplace ergonomic aspect into account [16]. The own studies have led to generation of necessary stages of effective design of ergonomic workplaces. A process of creation or improvement of the workplace should consist of the following stages [16]:

1) Development of the work method.
2) Determination of the spatial position of the operator, with consideration of his anthropometric features.
3) Planning of appropriate equipment of the manufacturing workplace.
4) Proper work organization (among other things: spatial arrangement of the workplace and time intervals for particular activities of the manufacturing process performed on the workplace).
5) Building a prototypic virtual model of the workplace.

The stages of ergonomic design of industrial workplaces with support of VR technologies were defined in a general manner (there will be a possibility to use them for design of various workplaces).

3.3 Methodology of creation of virtual workplaces

In a technical sense, each virtual workplace is a system consisting of an appropriate VR hardware (including stereoscopic projection systems, e.g. HMD or CAVE system, tracking and gesture recognition devices for interaction and / or haptic devices) and software. The software – a VR application – is always a heart of such a system. The "VR application" should be defined as one, closed entity (in the programming sense), containing virtual models of objects placed in a properly defined environment, ensuring the user with interaction and immersion.

Fig. 5. Stages of VR application development [17]

Stages of VR application development are shown in the fig. 5. The first stage is the CAD model transfer – it consists in conversion of the parametric solid or surface model created in the selected system to a polygon mesh (through a tesselation process) and then an import of the converted model to a VR environment. This stage also includes work related to improvement of 3D object appearance, by application of visualization techniques, such as texture mapping, lighting effects, reflections etc.

The main stage of creation of any VR application is programming of objects behavior. Standard object behaviors include mostly movement as a response to a user-generated event (mouse click, keyboard button press, entering the defined collision zone with hand or other body part of the user) or an event generated by another object. Other object behaviors are deformations (dynamical shape change) or changes in appearance (smooth change of transparency, color, texture etc.). Method of behavior programming highly depends on used software, frequently there is a possibility of utilizing methods of so-called visual programming, consisting in making connections between nodes exchanging data of various types. In any case, object properties must be set first (e.g. a kinematic node needs to be informed of the target position and movement velocity), then connections can be made.

Creating user interface is also an important stage of VR application development – the interface must be intuitive and allow easy launching of all the necessary functions of the virtual model. Almost always some form of the Graphical User Interface (GUI) is in use, in connection of traditional input devices (mouse and keyboard) or with tracking systems, where movement of user's hands, fingers, legs or heads are registered as input. In applications where user is expected to move around a room, 3D interface is often used, where buttons, sliders etc. take a form of animated 3D solid objects with defined collision zones [17].

The final stage is the application testing, verification of the studied workplace and possible further iterations (correction of the CAD model, performing import stage once again, object adjustment and testing functionalities again). Finished application may be used in the process of education of future operators of the workplace, which will shorten the time needed to introduce the operator to work on the new workplace with full efficiency.

4. Examples of applications

4.1. Workplace for stud welding

Prototype of the virtual stud welding workplace (fig. 6) is an example of approach with application of the haptic technology. Model of the workplace was prepared in a CAD system, according to guidelines prepared for the real manufacturing workplace. On the workplace, the following groups of activities can be performed:

- Device control (turn the welding machine on/off, table rotation, opening / closing the pneumatic clamps)
- Placing the semi-finished product (sheet metal) on the workplace
- Stud welding using a special tool (weld gun)

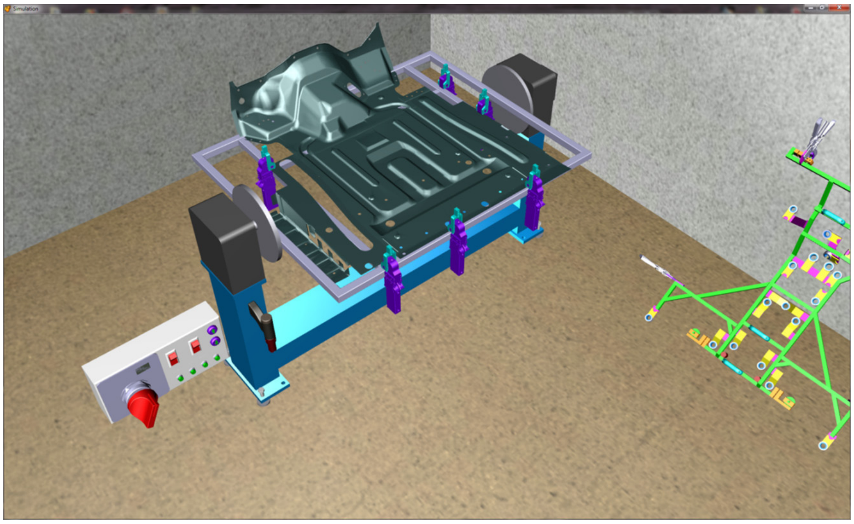

Fig. 6. Virtual stud welding workplace

Initially, the virtual workplace was destined to be used with the magnetic tracking system. Nevertheless, limited possibilities of testing of work ergonomics during welding with a weld gun was a factor that forced the decision of using the haptic device – Phantom Premium 3.0 manipulator. On the basis of the CAD model of the weld gun, a solid model was generated and subjected to adaptation by adjusting the inner shape to geometry of the haptic manipulator end effector (fig. 7). Then, the physical prototypes were prepared using additive technology of Fused Deposition Modeling, obtaining easy to assemble model of the gun (fig. 8).

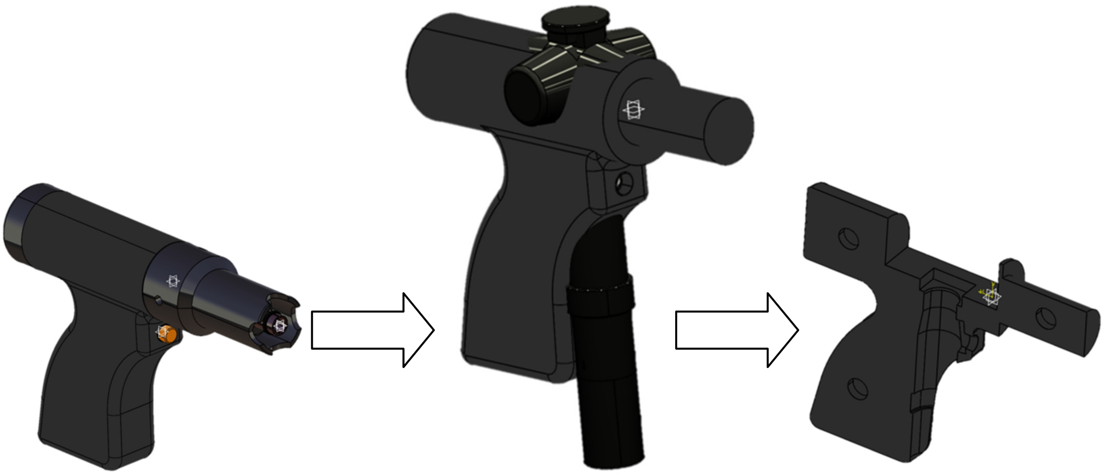

Fig. 7. Adaptation of the CAD model of the weld gun

Fig. 8. Physical model of the weld gun

Simultaneously, connection between physical and virtual representation of the tool was prepared. System of collision detection between the gun and its environment was implemented and expanded with the force feedback and position of the manipulator end effector was connected to position of the virtual gun. As a result, a complete application allowing to study various aspects of the stud welding process was created. The Phantom Premium 3.0 manipulator has workspace of comparable size to workspace on the stud welding workplace, so there were no practical limitations in testing of the welding process itself, however all the supporting activities (turning the devices on/off, placing the sheet metal on the working table) still had to be tested using regular hand tracking. Such a method of use of the real prototype connected with a virtual one was named a "hybrid approach" [17].

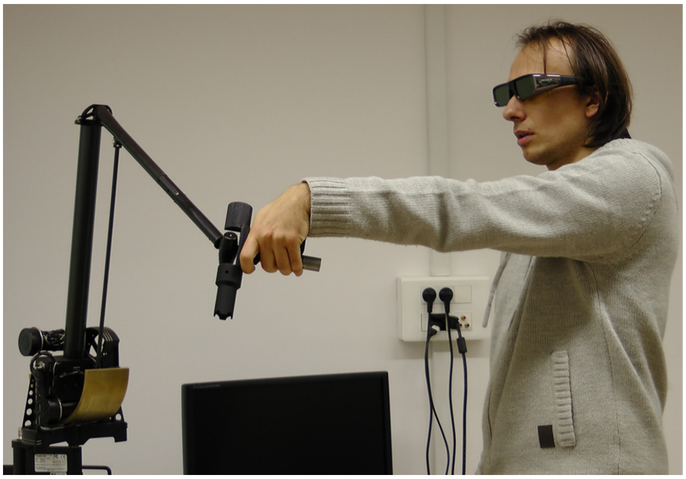

Fig. 9. Manipulation using prototype of the weld gun on a haptic device (visualization realized by stereoscopic large-screen projection system, not included in the photograph)

4.2. Drilling and assembly workplace

Prototype of a double workplace for drilling and assembly is an example of workplace prototyping with object tracking implementation. As a result of work in the CAD and VR environment, an interactive model of two workplaces was created (fig. 10). The two workplaces are joined – on the drilling work stand holes are made in one half of the pin coupling and the assembly work stand is used to join both the halves together with nuts and bolts. Aim of the work performed in the VR environment was to build a functional prototype of two workplaces as an environment to study the indirect interactions between two users immersed in the virtual scene.

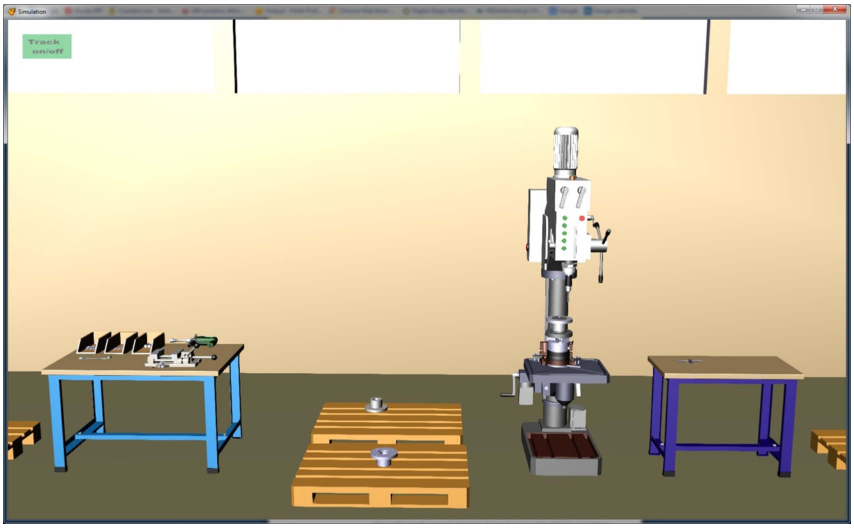

Fig. 10. Virtual workplace for drilling and assembly

The hybrid approach (mixing virtual models with real objects) was also used for this double workplace – it consisted in application of physical tool models (e.g. a wrench – fig. 11), used in the manufacturing workplace. In connection with the hand and head tracking and a gesture recognition device (fig. 12), a possibility of representing almost every activity performed on both workplaces was obtained (among other things: control of the stationary drilling machine, fixing and unfixing the pin coupling half, assembling two pieces of pin coupling together etc.)

Fig. 11. Physical model of a tool connected with the virtual environment by an optical tracking system marker

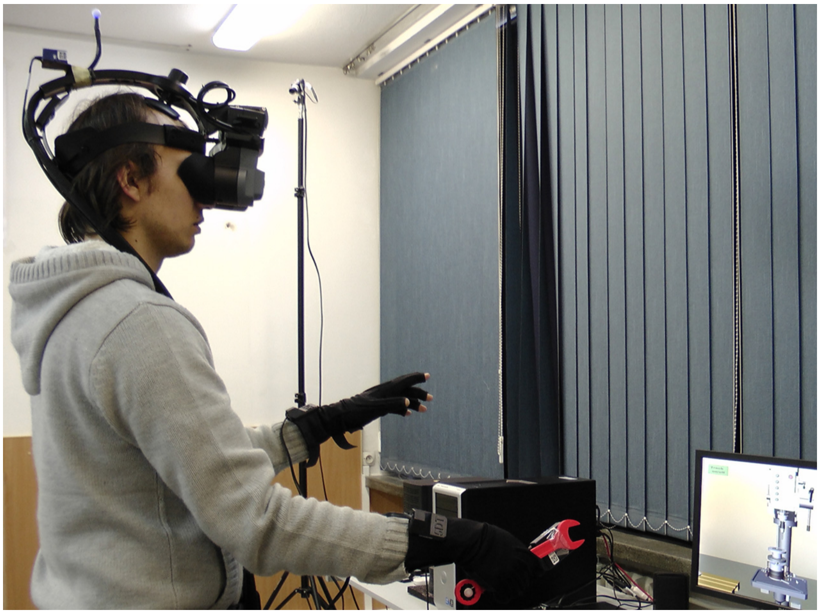

Fig. 12. Manipulation on the drilling workplace with application of hand tracking, gesture recognition gloves and a wrench model

5. Summary

Virtual prototypes of workplaces allow to perform a thorough analysis and optimization of solutions, mostly related to work safety, without need to build physical prototypes of workplaces, as it is done in a traditional way. Possibility of testing and simulation of many configurations of the "human-machine" system in the virtual research environment limits the costs of such studies and it is much safer to perform. Dangerous situations, threatening the operator's health may be tested without real machine. Thanks to this, a number of simulations risking an accident involving a human operator is limited.

Experience of the authors and other institutions dealing with VR application in manufacturing workplaces design allows to formulate some conclusions and generalizations. Available hardware VR systems have a large potential in scope of ensuring realism of created simulations (tracking and projection systems ensuring immersion and haptic devices giving the user a sense of touch and force response to his actions). Expanding the virtual models with physical prototypes (usually made by additive manufacturing technologies – 3D Printing or Fused Deposition Modeling) allows to additionally increase the realism of the user's feelings. Available authoring tools allow to program virtual environments of almost any level of complexity, both logical and graphical. VR systems allow to implement relations describing work of any device with taking its full functionality into consideration.

The virtual technologies described in the paper have their advantages and disadvantages. The main disadvantage of the immersive Virtual Reality (with personal projection and tracking systems) is the lack of the haptic feedback. On the other hand, haptic devices are immobile, so user cannot move around while using them. So the main disadvantage of these two technologies is that using them for workplace design simultaneously is limited. Probably the best solution for optimal results is to mix all the virtual technologies sequentially or concurrently (at the same time, but separately) – this will allow to explore all their advantages and prepare the virtual workplace that fulfills all the requirements.

Acknowledgements

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