Analysis of usability of the virtual reality technology for risk assessment in machinery design

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Abstract—The obligation to conduct risk assessment at the earliest possible stage of machinery design arises both from good engineering practices and legal requirements. The research conducted using Document Investigation an Expert Inspection method confirmed the usefulness of the VR technology for identification of mechanical hazards and for evaluating the possibility of access to particular elements of the machine. A model of anthropometric features of a human being have been very useful for Th as well as for assessing obtaining the data necessary for evaluating the stress on the musco - skeletal system. The final verification of the developed method will be performed by means of user testing (UT) method.

Keywords: risk assessment, virtual reality, safety of machinery

I. INTRODUCTION

The obligation to conduct risk assessment at the earliest possible stage of machinery design arises both from good engineering practices and legal requirements. According to the directive 2006/42/EC [1]:

“The manufacturer of machinery or his authorised representative must ensure that a risk assessment is carried out in order to determine the health and safety requirements which apply to the machinery. The machinery must then be designed and constructed taking into account the results of the risk assessment. By the iterative process of risk assessment and risk reduction referred to above, the manufacturer or his authorised representative shall:

- determine the limits of the machinery, which include the intended use and any reasonably foreseeable misuse thereof,
- identify the hazards that can be generated by the machinery and the associated hazardous situations,
- estimate the risks, taking into account the severity of the possible injury or damage to health and the probability of its occurrence,
- evaluate the risks, with a view to determining whether risk reduction is required, in accordance with the objective of this Directive,
- eliminate the hazards or reduce the risks associated with these hazards by application of protective measures”

This requirement imposes on the machinery manufacturer a direct obligation to carry out risk assessment.

General principles of risk assessment are set forth in the norm ISO 12100:2010 “Safety of machinery. General principles of design. Risk assessment and risk reduction” [2]. The procedures and principles of conduct described in that norm show the importance of carrying out a systematic risk assessment and of its proper documentation. The specific character of these activities indicates the use of computer solutions as tools supporting risk assessment. For that reason designing such tools is becoming more and more popular. E.g. methodologies of risk assessment at work stations (e.g. a computer tool called STER) have been developed in CIOP-PIB (Central Institute for Labour Protection - National Research Institute) and successfully used. Computer tools supporting risk analysis have been developed also for the purposes of machinery design [3].

Practical experience gained in the course of carrying out risk assessment on the stage of designing production systems presented in [4] showed that even not particularly detailed virtual models of automated production systems may considerably improve certain stages of risk assessment. This experience found its confirmation during development of a method of virtual modelling of hazard areas the purpose of which was to support the selection of protective equipment for machines [5]. The purpose of the research was to use the state-of-the-art computer technologies for streamlining the process of risk assessment conducted by machinery designers.

II. APPLICATION OF THE IRTUAL EALITY (VR) TECHNOLOGY IN THE FIELD OF SAFETY

A. Advantages of the VR technology

Virtual reality (VR) is an image of an artificial reality created with the use of IT technology. It consists in a multimedia creation of a computer representation of objects, space and events. It can present both the elements of the real world (computer simulations) as well as of a completely fictional one. There are two concepts of virtual reality:

- Immersion is the ability of a computer-generated environment to create an impression that the user is a part of that artificial environment and is “submerged” in it. The sensation of immersion is achieved through at least an impact on at least the sense of sight by means of a stereoscopic projection of two different images for the left...
and for the right eye. The difference between these two images consists in a different point of observation. Both are generated in such a way that the point of observation of each one of them reflects the way in which human eyes naturally register images. Images may be displayed on two displays at the same time or alternately, or they may overlap on one and the same display. More advanced systems offering a better quality resulting from faster processing of information and a more precise rendering of image and sound, generate the environment which is easier for the user to assimilate. This is very important for the comfort, ergonomy and safety of work.

- **Interaction** is a term which defines the mode of operation of a computer system consisting in maintaining a continuous contact with the user (by exchanging the information about the position and the instructions). The information is exchanged continuously and has a direct impact on the performed tasks and on the displayed information. In the VR environment the interaction is broadened with the feedback from the system which may have various forms depending on the tasks performed on peripheral devices.

The most important attributes of virtual reality which determine the possibilities of application are the following [6]:

- the environment is computer-generated,
- the environment and user's sensations are three-dimensional,
- the user has a sense of presence in the virtual environment,
- the user can move in the virtual environment,
- the objects in the virtual environment behave in the same way as in reality,
- there is a real time interaction between the user and the virtual environment.

These features of the virtual reality technology allow such systems to carry out more effective analyses than those carried out by the commonly used CAD/CAM systems. The architecture of these systems allows better adaptation to the user's needs. At the same time VR presents real objects better than CAD/CAM systems. These features substantiate the assumption that VR may effectively support the risk assessment carried out by machinery designers.

**B. VR technology versus safety**

The methods of using virtual reality technologies (research using advanced computer simulation methods) have been developing extremely dynamically all around the world. The works devoted to application of this technique to analysis of safety of industrial systems are being carried out in many centres in the world. In the USA the most advanced works of this type are conducted e.g. by the Department of Health and Human Services, Centre of Disease Control and Prevention NIOSH. They apply to the use of virtual modelling for ergonomic analysis and risk assessment at work stations in mines. The application of these techniques in assessment of the risk related to natural disasters is presented in [7]. In [8] Kim and Gong presented the principles of using the VR simulation for assessment of the risk of collision in the sea transport. In the EU an Integrated Project called VIRTUALIS (Virtual Reality And Human Factors Applications for Improving Safety [9]) has been conducted under 6PR. As part of this project the methods are being developed of using virtual modelling for taking into account human factor in designing the process installations, in particular in the chemical and petrochemical industry. In [10] the possibilities of application of the VR technology in research work concerning the effectiveness of warning signals are presented. The use of virtual reality technology for analysing safety at the construction site and for supporting trainings is presented in [11]. [12] presents a concept of application of VR simulators in safety trainings for lift truck operators, whilst in [13] the use of virtual simulations for selecting visual systems for machines is discussed. Research has also been conducted with respect to using enriched reality systems to increase safety in work stations. Examples of such applications are presented in [14]. General principles of using virtual reality techniques in the field of safety are discussed in [15] and [16]. Examples of application of VR in the area of safety and ergonomy are presented in [15]-[17]). The research in this area is conducted for example with respect to the needs of nuclear power stations were VR systems allow searching for personnel in emergency situations. The application of VR technologies seems to be particularly advantageous where training in real conditions carries with it a threat to human life and health. For this reason trainings in virtual environment are most usually conducted in such fields as medicine (e.g. virtual operations [18]) or atomic power industry (e.g. limitation of employee's exposure to ionizing radiation [19]). Research with the use of VR technologies is also conducted with respect to the operation of specialist machines, e.g. in mining applications [20]. VR technologies are used for the analysis of work ergonomy (e.g. in the case of operation of machines in mines [21]) and for identification of possible hazards (e.g. related to the work in a mine [21 and 22]). This research allowed to identify the possibilities of application of VR technologies in various aspects of analysing and increasing the safety.

The general concept of including the aspects of safety in the process of designing industrial equipment is presented in [23] and [24]. The first important step towards the application of computer technologies for safety analyses in the course of machinery design was the development of the Computer Aided Safety Standards Application for Design (CASSA) system [25]. This tool supports a machinery designer in analysing the possible scenarios of events taking into consideration safety aspects. For that purpose special, user-oriented interfaces were used, adapted to carrying out various types of analyses. The tool takes into account also various types of users such as machinery designers or standardisation group experts. These tools indicate that application of 3D modelling in risk assessment on early stages of machinery design is very effective.

All the previous research dealt with the issue of using computer technologies for risk assessment in detailed aspects, usually with respect to the ergonomy of work stations. In the available literature there is no information about any attempts to use the virtual reality technology for carrying out risk assessment in accordance with the machinery directive by taking into consideration all of its aspects. The process of risk assessment carried out by a machinery designer has different objectives and uses different methods of operation than e.g.
ergonomic analysis of work stations in the process industry described in [9]. The risk assessment method which will be analysed as part of the project will be oriented at streamlining the process of risk assessment required by the machinery directive, taking into consideration the specific character of machinery design. This will make it possible to systematise the operations related to risks assessment. Improving the risk assessment process and making it possible to carry out risk assessment already on early stages of machinery design will also reduce the costs connected with application of protective systems for reducing the hazards occurring at the machine. The project concerning the development of the methods of using VR systems for carrying out risk assessment in the course of machinery design is a natural continuation of the hands-on experience [4] as well as the research work conducted so far [3], [5], [13].

C. Risk assessment carried out by machinery designers

Risk assessment is a process which allows to obtain the most important information necessary for taking the decisions on safety assurance methods. It is an iterative process which should be performed on individual stages of the machinery life cycle. Its results depend, to a large extent, on the stage of life cycle on which the process is being conducted. Risk assessment carried out by a designer allows to gather detailed information about the construction of the machine and its functioning and identify the information which is important for the user.

The basic principles of risk assessment have been specified in the norm ISO 12100:2010 [2]. Fig. 1 presents a diagram of a general methodology of carrying out risk assessment methods specified in those documents. The operations conducted under the risk assessment procedure include:

- identification of the machine,
- establishment of the limitations related to the machine,
- identification of hazards,
- risk assessment,

In the case of an unsatisfactory result of risk assessment the designer is obliged to apply proper measures to reduce the risk. Generally, risk reduction is not a part of the process of its assessment and therefore it is not covered by our analysis. The issues related to the use of the VR technology in the risk reduction process are presented in [5].

Risk assessment must be carried out independently for every identified hazard. In the case of various hazards, different risk assessment methods may be used. For assessing the level risk matrices,

- risk graph,
- numerical calculations,
- numerical scores,
- qualitative methods,
- control lists,
- measurements,
- combinations of the above-listed methods.

Usually, the specific character of hazard determines the method of risk assessment. For that reason risk assessment is carried out with respect to every hazard independently.

All the activities carried out in connection with risk assessment should be documented. The documents on risk assessment should contain the information on the applied procedure and the obtained results. This documentation, depending on the machine being examined, should contain:

- identification of the machine,
- assumptions with respect to the operation of the machine,
- description of identified hazards and hazardous situations,
- description of risk reduction measures applied on successive stages of design,
- information on residual risk,
- results of risk assessment.

III. METHODOLOGY OF RESEARCH

The purpose of the research conducted was to establish the usefulness of virtual reality technologies for a specific application, that is for carrying out risk assessment on the stage design of machinery. The available literature contains the information on a series of Usability Evaluation Methods (UEMs). The most popular ones include:

- document-based inspection (DI),
- expert inspection (EI) and
- user testing (UT).

Evaluation of effectiveness of these methods is presented in [26].

DI is a usability evaluation method which consists in analysing the documents on the requirements which must be met and the properties of the evaluated solutions (ISO / TS 16982 [27]). The DI method is used in many variants (cognitive analysis, compliance with norms and guidelines, compliance with the requirements of ergonomy [28], etc.). Effectiveness of this method depends on the organisation of the conducted analyses. A significant limitation to this method is the fact that it can be used only for evaluation of the already known solutions, in accordance with the current know-how. Skills of the experts applying this method are also important.

Fig. 1. Overall methodology of risk assessment
EI is a popular method of evaluation which finds application particularly in industry. It is an informal method consisting in evaluation based on the experience and knowledge of one or more experts. The experts diagnose potential problems based on the latest knowledge and their experience. This allows a relatively easy identification of potential limitations in the usability of the examined solutions. The limitation in the case of this method is the fact that it allows to predict only the problems known from previous experience.

The most well-known method is probably UT. It consists in practical testing of application of the developed solutions by their potential final users. The purpose of these tests is to gather spontaneous comments about the usability of the suggested solutions, as well as to conduct an evaluation on the basis of measurable indicators such as task performance time, accuracy of achieved results or the number of errors made.

The evaluation conducted in [26] indicated that individual methods differ both from the point of view of their effectiveness and the type of the detected problems. For this reason in this project all three methods will be used in turns.

On the 1st stage the DI method will be used to evaluate the potential usability of the VR technology in assisting risk assessment in the course of machinery design. Attempts will be made to carry out such evaluation with respect to the requirements of ISO 12100:2010 [2] on the basis of the documentation of 3 machines. The purpose of these attempts will be to establish on which stages of risk assessment the application of the VR technology might be useful. Various methods of assessment of the risk related to various hazards will be analysed. In order to get a greater certainty about the usability of VR, analyses will be conducted with the use of the PRO-M software [3] which guarantees regularity of tasks. The analyses will be performed by the experts who have wide experience in the risk assessment related to the use of machines as well as knowledge about the VR technology [4, 5, 12]. The results of the conducted analyses will form the basis for development of a draft method of using the VR technology for supporting the risk assessment procedure carried out by machinery designers.

On the 2nd stage, the analyses will be conducted by means of the EI method. For that purpose virtual models of three machines will be built. A team of experts will conduct tests of assessment of the risk related to their operation. The purpose of these tests will be to identify possible problems with the usability of the proposed methods as well as to suggest the ways in which these problems might be eliminated.

The final verification of the developed method will be conducted on the 3rd stage by means of the UT method. The developed method will be presented to the machinery designers who will try to apply this method to the currently designed machines. After that they will evaluate the usability of the proposed method.

In the process of analysing the methods of assessing the risk connected with various threats the PRO-M software has been used, developed in order to support machinery designers in carrying out such an assessment [3]. The basic features of this software are presented in [3]. The PRO-M software has been developed to simplify and formalise the operations of machinery manufacturers connected with carrying out and documenting risk assessment on the stage of machinery design.

All the activities have been conducted in close cooperation with the company specialising in machinery design.

IV. RESEARCH RESULTS

A. Assignment of VR technology to hazards

The research began with analysis of the risk assessment methods, used by machinery manufacturers, from the point of view of application of virtual reality technologies. The purpose of the analyses conducted by means of the document inspection (DI) method was to develop a matrix of assigning hazards to the functions realised by as simple as possible hardware and software configuration of the virtual reality technology, in the process of risk assessment conducted by machinery designers.

The research consisted in attempts to conduct risk assessment with respect to the requirements of ISO 12100:2010 [2] on the basis of documentation of 3 machines. Various methods of assessment of the risk related to various hazards were analysed. In order to get a greater certainty about the usability of VR, the analyses were conducted with the use of the PRO-M software [3] which guaranteed regularity of tasks. The analyses were performed by the experts who have wide experience in risk assessment related to the use of machines [3] as well as knowledge about the VR technology ([4] and [5]).

In order to select the machines whose documentation was analysed, over 150 various machines designed and built in the last few years had been examined. These included, first of all:

- multi-station assembly and production lines,
- automatic assembly lines,
- final product control testers,
- machines and equipment for production of foil packaging,
- automatic packaging lines,
- machines for automation of feeding, etc.

Initially, 12 machines were selected from among them for further analysis:

- glass lift assembly stand,
- trimmer for windowpane dividers,
- automatic bearing assembly press,
- stand with a rotational windowpane dividers,
- assembly line for clamps,
- final control tester,
- connector auto cutting machine,
- automatic brush holder assembly machine,
- sleeve control device,
- automatic nipple assembly machine,
- leak testing stand,
- automatic spoke feeder.

These machines were analysed from the point of view of hazards and of their usefulness for risk assessment methods. In the end, the machines shown in the Drawing 1 were selected for the research:

- automatic nipple assembly machine,
On particular stages of risk assessment the experts analysed the features of the VR technology from the point of view of its usability in the conducted activities. As a result it was established that application of the VR technology can be very well grounded. The VR technology is particularly useful for determining the limitations related to the machine and identification of threats and hazard areas. This applies in particular to mechanical and ergonomic threats as well as threats related to malfunctioning of control systems. In this last case the VR technology can be useful for determining the functional requirements with respect to individual safety functions but it will rather not find application in the process of determining the requirements concerning the resistance to defects or in the evaluation of the achieved safety integrity level (SIL) and performance level (Pi).

The VR technology is slightly less useful in the process of risk assessment, however, in some cases the analyses indicated that it may assist the designer also in this area.

The analyses show, however, that the usefulness of the VR technology is insignificant if the risk is assessed by means of the method consisting in measuring the machine parameters and comparing the results with criterial values. This applies to such hazards as:
- noise,

### TABLE 1. MATRICE OF ASSIGNING HAZARDS TO THE FUNCTIONS PERFORMED BY THE VIRTUAL REALITY APPROACH IN DIFFERENT RISK ASSESSMENT STAGES

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Risk assessment method</th>
<th>Risk assessment and risk reduction stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>determination of the limits of the machinery</td>
<td>hazards identification</td>
</tr>
<tr>
<td>mechanical</td>
<td>hybrid</td>
<td>HU</td>
</tr>
<tr>
<td>electrical</td>
<td>check list</td>
<td>U</td>
</tr>
<tr>
<td>hazardous agents (noise, vibration, radiation, hazardous materials and substances etc.)</td>
<td>measurement</td>
<td>SU</td>
</tr>
<tr>
<td>explosion</td>
<td>applied materials analysis</td>
<td>SU</td>
</tr>
<tr>
<td>due to malfunction of control system</td>
<td>risk graph</td>
<td>HU</td>
</tr>
<tr>
<td>due to ergonomics</td>
<td>calculation of risk factors</td>
<td>HU</td>
</tr>
<tr>
<td>due to working environment</td>
<td>risk graph</td>
<td>SU</td>
</tr>
</tbody>
</table>

HU – highly useable, U – useable, SU – small useable
- vibration,
- dust,
- dangerous substances,
- radiation, etc.

Table 1 presents a matrix of assignment of the usability of the VR technology to hazards.

Analyses of the example of an unfinished machine show that the VR technology can be particularly useful for identifying the risk which could not have been reduced by its manufacturer, since it depends on the final construction of the machine.

Assessment of usability of the VR technology for supporting the risk assessment process, made by means of the documentation inspection (DI) method, was carried out independently by 2 experts specialising in machine safety and experienced in the use of virtual environments. The important thing here is the fact that conclusions of both experts coincided.

B. The use of the VR technology for risk assessment

The next step consisted in the development of a risk assessment method with the use of virtual reality technologies. The research was conducted by means of the expert inspection (EI) method. The analysis was performed with the use of the models of 3 machines made in the VR technology. The team of experts conducted tests of assessment of the risk related to their operation. The purpose of those tests was to identify possible problems with the usability of the proposed methods as well as to suggest the ways in which they might be eliminated.

For presentation of the virtual environment the OGRE3D (Object-Oriented Graphics Rendering Engine; www.ogre3d.org) library was used. Detection of collisions and simulation of physics was conducted by means of a popular Bullet motor. The analysis was performed mainly with the use of the projection technology. The tests were performed both by means of a laptop computer and a large screen projection with a 3D projector.

For carrying out the risk assessment in the projection method a model of anthropometric features of a human being was used, prepared by CIOP-PIB. The model, showed on fig. 2, was modified by introducing the functions which make it possible to simulate the work and collect the data necessary for assessing the load of the muscular and skeletal system.

Attempts to apply the immersion technology were also made, with the use of a video tracking system, wired gloves and HMD system.

Then, a method of creating VR models of machines on the basis of their CAD3D documentation was developed. This method uses generally-accessible FreeCAD, MeshLab, Blender3D and TrollViewer software, available on a license-free basis. This method was used to build VR models of 3 machines:
- tester of car glass lift (Drawing 3)
- bearing transport system (unfinished machine)
- automatic machine for cartridge regeneration

The performed analysis revealed that the most convenient system for supporting the risk assessment conducted by machinery designers is the VR projection system, especially when a laptop computer is also used. The immersion system, on the other hand, turned out not to be very useful.

The developed method of using the projection system together with a modified model of a human being is particularly useful for determining the limitations related to the machine with respect to defining the access areas necessary for operation, maintenance and repair of the machine. This method is especially useful for analysing the fulfilment of ergonomy requirements with respect to:
- checking the access to operation areas, maintenance areas and control elements,
- obtaining the data necessary for evaluating the stress on the muscular - skeletal system.

It may also be used for verification of the effectiveness or reducing the risk connected with mechanical threats, but in this case the application of the method of modelling hazard areas and accessible areas, described in [5], is more suitable.

V. SUMMARY, CONCLUSIONS

Risk assessment should be carried out in accordance with ISO 12100:2010 [2] and the methods recommended in that norm. The purpose of using the VR technology is to facilitate the procedure of risk assessment as well as to make it possible to collect the data necessary for such assessment. As it follows from the conducted research, the model of anthropometric features of a human, together with a developed method of determining the parameters necessary for evaluating the stress on the muscular and skeletal system, provide particularly helpful support for risk assessment. Adaptation of the developed model to the norms standardised with respect to the Directive 2006/42/CE allows it to be used in the process of evaluating the compliance of machines which may be difficult in the case of using other available models oriented at evaluation of the work station to which the machine belongs.

The research also confirmed the conclusions drawn on the previous stage and indicating the usefulness of the VR technology for identification of mechanical hazards and for evaluating the possibility of access to particular elements of the machine.

The proposed method of creating a VR simulation was oriented at such a selection of IT tools which would not entail a
The problem of integration of various software environments was another issue. As it has been shown on the example of the three machines, transfer of the data from a CAD software does require a certain amount of work, but if the proposed software is used, such a transfer is relatively simple. Also the proposed model of anthropometric features of a human being can be read by the VR environment presentation software. Unfortunately, the PRO-M software does not have the interface which would make it possible to read text files generated by the VR software; however, introducing the read data directly into the PRO-M software is very easy. Furthermore, the PRO-M software has been used as an example. Every machinery designer can use other methods of risk analysis, e.g. filling out company forms developed precisely for that purpose.

The final verification of the developed method will be performed by means of user testing (UT). The developed method will be presented to the machinery designers who will try to apply this method to the currently designed machines. After that they will evaluate the usefulness of the proposed method, also from the point of view of its adaptation to the companies specialising in machinery production.

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