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




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Human-Centric Design of Automated Production Lines Using Virtual Reality Tools and Human Data Analysis

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Abstract. The 4.0 revolution is leading to increasingly automated, flexible, and intelligent manufacturing systems that require greater complexity to manage during maintenance and process control. In this context the optimization of the human-machine interaction plays a crucial important role in the design of modern industrial systems. Virtual Reality (VR) offers realistic simulation environments where users can be involved to replicate specific human tasks, detecting and solving problems before they occur. The paper proposes a human-centric digital design methodology that integrates VR technologies with human data analysis tools to support the design or redesign of complex industrial systems. Different wearable devices have been used to collect data about physical and mental user conditions to provide an early assessment of the operators’ workload, while comparing different design solutions into the virtual space. An industrial use case related to the redesign of packaging automated machines was used to validate the proposed method and tools: a preliminary correlation between physiological parameters and machines interactions was found.

Keywords: Human-centred design · Virtual Reality · Human data analysis · ergonomics and human factors · digital simulation

1 Introduction

Industry 4.0 (I4.0) paradigm has brought a real revolution in production sites and manufacturing systems, introducing a set of key-enabling technologies [1] to enhance the flexibility and to speed up the production. Despite this great advancement in innovation, humans are still at the core of many industrial processes, due to their inner flexibility and capacity to adapt to new operations without disrupting the production environment [2]. Recently, the Industry 5.0 idea [3] introduces the concept of human centrality as a success factor in modern factories to achieve a more sustainable and resilient system, placing the wellbeing of the operators at the centre of the production process. In this

context, it is crucial to integrate humans with advanced technological systems at the shop floor, increasing at the same time the level of the workers' wellbeing and the system performance [4]. To achieve this result, technologies like virtual reality (VR) and human data analysis tools are particularly helpful to integrate ergonomics and human factors into the design of complex systems that can be tailored to operator characteristics and needs. Moreover, such technologies can help companies to limit the waste of resources due to the reduction of physical prototyping.

This paper proposes a Human-Centred Design (HCD) methodology to effectively redesign complex systems or machines by combining VR and wearable devices to collect data about physical and mental human conditions and virtual spaces to provide an early assessment of the operators' workload. This methodology was applied in a real case study concerning maintenance and routine operations on an automatic machine for packaging.

2 Research Background

In the last few years, the assessment of ergonomics in manufacturing has continuously increased: nowadays process design concerns not only task planning and layout design, but also the operators' physical and psychological comfort, which have been proved to be strictly connected with factory productivity [5]. So, ergonomics could be an opportunity to enhance the level of modern flexible and advanced manufacturing systems, usually characterised by a significant amount of manual work. Maintenance and routine operations on complex machines or systems are most of all critical because engineers and designers focus primarily on system performance rather than on its maintainability. In order to overcome these issues, VR simulations are particularly helpful because it is possible to immerse operators in a virtual environment and to simulate its actions and reactions in order to test their experience in advance [6]. This approach is usually known as virtual manufacturing (VM), in which the human actions in the virtual scene can be recorded to collect information and find out ergonomic issues. Contrarily to traditional desktop-based digital human simulations (DHS), the use of VR allows to include the assessment of cognitive aspects, such as human reliability, human errors, decision-making, until the quality of the operational performance [7]. Alongside this topic, recent research works started developing platforms for human data collection, post-processing and correlation in an integrated way, supporting factory ergonomics by monitoring human activities [8]. In particular, the analysis of humans' physiological parameters such heart rate (HR), heart rate variability (HRV) or blood volume pulse (BVP), eye activity e.g., pupil diameter (PD) or blink rate, brain activity by EEG data, breathing rate (BR), galvanic skin response or electrodermal activity (GSR or EDA) can indirectly reveal possible criticalities for operators linked to their mental workload [9].

In the recent literature, many approaches to carry out an early assessment of human workload using DHS and VR technologies were proposed. For instance, Caputo et al. [10] proposed an appraisal of a workplace design and ergonomics validation procedure based on DHS to solve ergonomic risks during the design phase in assembly lines. Similarly, Zhu et al. [11] demonstrated the application of DHS can improve the realism and effectiveness of VM, including human factors and ergonomics in various fields of application. Kačerová et al. [12] founds that the combination of VR technology and MoCap

systems allows the ergonomic evaluation of an assembly workstation, and this approach is more accurate than standard methods. These methods are surely innovative, but all primarily focuses on physical evaluation and slightly consider the cognitive counterpart. To overcome this issue, Peruzzini et al. [13] developed a protocol analysis to assess both physical and cognitive workload on digital models to support ergonomics workstation design. The challenge is to bring HCD approaches, considering both physical and mental human performance, at a practical level to leverage VM and explore how to help the system design process.

3 Methodology

The proposed methodology aims at supporting engineers during the design (or redesign) of complex systems like automatic machines, using a human-centred vision is mandatory to prevent design errors and to promote the workers' wellbeing during maintenance and operational tasks. The methodology is inspired by the User Experience Design (UXD) cycle, as shown in Fig. 1, and structured in 4 phases are listed below:

1. User research: analysis of the human-machine interaction during the current situation, on the as-is system, to map the as-is interaction and collect useful data. Digital simulation is adopted to post-process the collected data, to give an ergonomic value for the as-is design and to set the redesign objectives. This phase ends with the definition of the users' requirements and of project goals;
2. Design: considering the interaction issues as detected in phase 1, engineers apply design changes (e.g., machine layout, components' positioning, reciprocal position between the operator and the machine, task execution modalities) in order to better fit ergonomic principles, to achieve a to-be design;
3. Virtual prototyping: a VM simulation of the to-be machine is realized by using VR tools and the novel human-machine interaction is simulated into the virtual environment involving real users to check the new process as designed;
4. Ergonomic assessment: using the VR simulation, the users can replicate the tasks under assessment into the virtual scenario and be monitored using motion capture system and human data wearable sensors. Physical and cognitive assessment can be carried out during the simulation by proper indexes (e.g., EAWS - European Assembly Work Sheet, NAS - Numerical Analogue Scale for stress) to compare as-is and to-be solutions. If the ergonomic assessment does not fully satisfy the user requirements and project goals, the process returns to the design phase and the cycle is repeated until a successful assessment.

During phase 1, the operators are monitored on the field by using the following tools:

- Tobii Pro Glasses 2: wearable eye-tracking device that can be used for various research applications, such as human behaviour and visual attention;
- Beslands SF-500 Dynamometer: digital force gauge capable of measuring pushing and pulling forces up to a maximum of 500N;
- Empatica E4 Wristband: medical-grade wearable device that unobtrusively monitors real-time physiological data, including BVP and EDA, skin temperature, and also movement due to the presence of a three-axis accelerometer.

During phase 3, the VM simulation is realized by involving the following hardware and software tools:

- HTC Vive Pro Eye: 6DOF wearable HMD equipped with 32 markers for 360-degree tracking, a G-sensor, a gyroscope and infrared tracking system, allowing monitoring of exact positions in the space;
- Leap Motion Controller: HCI (Human-Computer Interaction) system that accurately captures hand movements allowing interaction with digital content;
- Unity 3D: cross-platform graphic engine that enables the development of video games and simulations as VR experiences (using SteamVR);
- Vicon cameras: motion capture system that uses infrared cameras and passive reflective markers on the whole body, which allows accurate real-time recording of three-dimensional movements;
- Siemens Tecnomatix® Jack 9.0: software for DHS which allows to import virtual mannequins in a digital environment and carry out ergonomic analysis;
- EAWS Score Calculator: excel worksheet which, through the postures (numerical values of the joint angles) obtained from the Jack software, calculates the EAWS score [14] of the entire task.

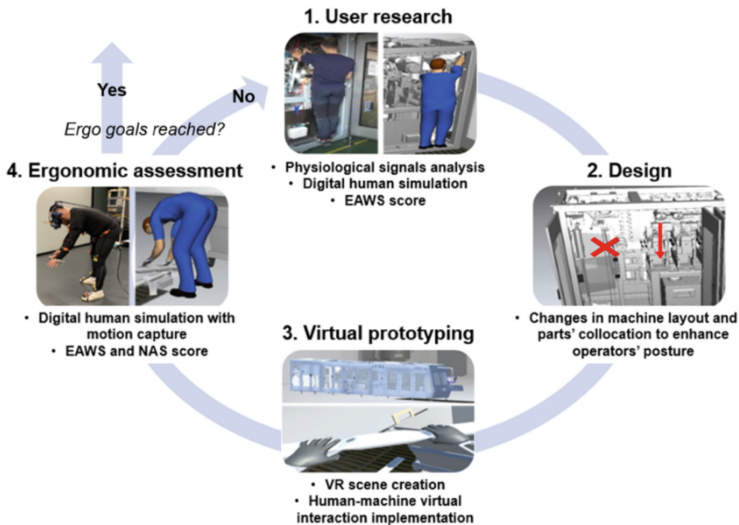


Fig. 1. Phases of the proposed methodology.

4 Industrial Use Case

The use case has been developed in collaboration with a global leader in the design of automatic machinery for beverage packaging. In particular, the aim of the use case is the design optimization of a specific machine to reduce the operators' workload during

maintenance procedures and routine tasks. The analysed task concerns the insertion and unrolling of the packaging material (i.e., a special material composed of paper, polyethylene plastic and aluminium) through the direct injection moulding module of a packaging machine. In particular, the analysis is carried out on the operator during the unrolling operation of the packaging material from the first bending roller through the six stations up to the last bending roller of the module. This procedure is usually performed by the operator every 30 min and requires about 10 min to complete the task. In the next sub-sections, the main steps of the proposed methodology applied to the presented industrial case are shown.

4.1 User Research

This phase involved an operator from the company, with more than 3 years of experience in the field, acting on the as-is machine to complete the task (i.e., refill of the packaging material) in the company machines test area. The participation was voluntary: no reward was given, and an informed consent was signed before starting the analysis. No corrective lenses were provided to the operator, and according to the given consent no cardiac issues were reported. The task was performed while wearing the Empatica E4 and Tobii Pro Glasses 2 devices. After a short calibration of the eye-tracking system, 3-min of signal recording from the wearable sensors in resting condition (upright, being still) were established at the beginning of the task execution to define the baseline of each physiological signal. A video camera recorded his movements during the task execution. Thanks to the dynamometer, the forces applied by the operator during demanding activities were measured. The post-processing phase focused on the operator's physiological data analysis: for instance, HR, EDA and PD data were graphed in time-domain to understand the main criticalities during the procedure. Data analysis was carried out highlighting the most significant trends in parameter variation, in the same way as reported in [15]. Moreover, the DHS of the considered task was modelled in Jack Siemens with different percentile from different male populations (i.e., 5th Thai, 50th German, 95th Dutch) in order to extract postures and to carry out the physical ergonomic evaluation through the EAWS Score Calculator [16]. Finally, the comparison between the physiological parameter trends and EAWS score distribution along the entire task allows the individuation of the main issues to solve in the redesign phase, such as incongruous postures, poor visibility and reachability, dangerous behaviours. In the considered task, the main issues detected referred to: 1) poor accessibility to the internal part of the machine; 2) poor reachability of the upper bending rollers and the lever, which lead to dangerous behaviours of operators; 3) uncomfortable postures during maintenance.

4.2 Design

A set of redesign actions were defined considering the ergonomic issues detected in the previous phase, to solve the problems without influencing the machine performance. As a result, they improved the accessibility adding a large platform on the base of the machine that helped the operators during the process in reaching high bending rollers. In addition, this change promoted a safer behaviour since a more stable foot placement zone was guaranteed. Engineers also introduced sliding doors to improve the accessibility to

the injection stations, which is the most time-consuming area of the entire task. Finally, the rollers release pressure lever was repositioned to be reachable during the process without moving on the other side of machine.

4.3 Virtual Prototyping

The new 3D CAD model of the to-be machine was imported as a.fbx file in Unity 3D and the VR scene was developed, introducing a set of scripts that allows user to interact with the virtual machine. The behaviours of objects in the scene were defined considering their role in the simulation: machine parts involved in the maintenance process were made interactable thanks to Leap Motion SDK, in order to have a realistic virtual experience. Finally, the virtual scene was developed for the HTC Vive Pro Eye headset.

4.4 Ergonomic Assessment

A set of tests were carried out in Lab within the developed VR scene involving a sample user performing the task in the virtual environment. Collected human data about body positions and movements were streamed from Vicon software to Jack Siemens software to virtualize the operator with a virtual manikin. The postural data files are exported from Jack Siemens into a semi-automated worksheet [16] and evaluated through EAWS ergonomic index and compared to the first step (the current machine version, as-is). The cognitive one, is evaluated by NAS stress questionnaire and the analysis of human physiological data trends. The results of the comparison of the human physical performance on the as-is and to-be design are reported in the next paragraph.

5 Results and Discussion

A synthesis of the results obtained by the post-processing of the operator's physiological data and postural analysis during task execution is shown in Table 1 and Fig. 2, according to the selected ergonomic indexes (i.e., EAWS, HR, PD and EDA). Table 1 sums the results of the comparison between the as-is machine and the to-be machine in term of EAWS score. It shows a significant reduction in the ergonomic value (especially for 50th and 95th percentile population), enhancing the workers wellbeing and reducing the risk of developing musculoskeletal disorders.

Table 1. Comparison between current and new machine model in term of EAWS score.

Percentile and population	EAWS score as-is	EAWS score to-be	Improvements %
50 th German	92,3	61,5	-33,37%
5 th Thai	65,0	64,4	-0,92%
95 th Dutch	61,7	41,1	-33,39%

In Fig. 2, experimental correlations were found between the HR and PD parameters, while the EDA graph was omitted since it didn't show significant trends in any sub-task.

Concerning the HR parameter, it showed a significant increase during the most physical subtasks, such as the unrolling of the packaging material in the first bending rollers and in the last ones at the end of the module, while a relevant decrease was reported while the operator was waiting for the completion of machine's automatic procedures and during tasks that were primarily mental demanding, such as the material insertion in the injection stations. As for PD, it showed an increase during the execution of the most physical activities and where greater cognitive effort were required. Similarly to HR, PD decreases in moments of rest due to the activation of the parasympathetic nervous system (PNS). Both reported the analogous trends especially where a high physical effort was required: at the contrary, the activity was primarily static (not physical demanding) at the entrance of the injection stations while more cognitive during the material insertion.

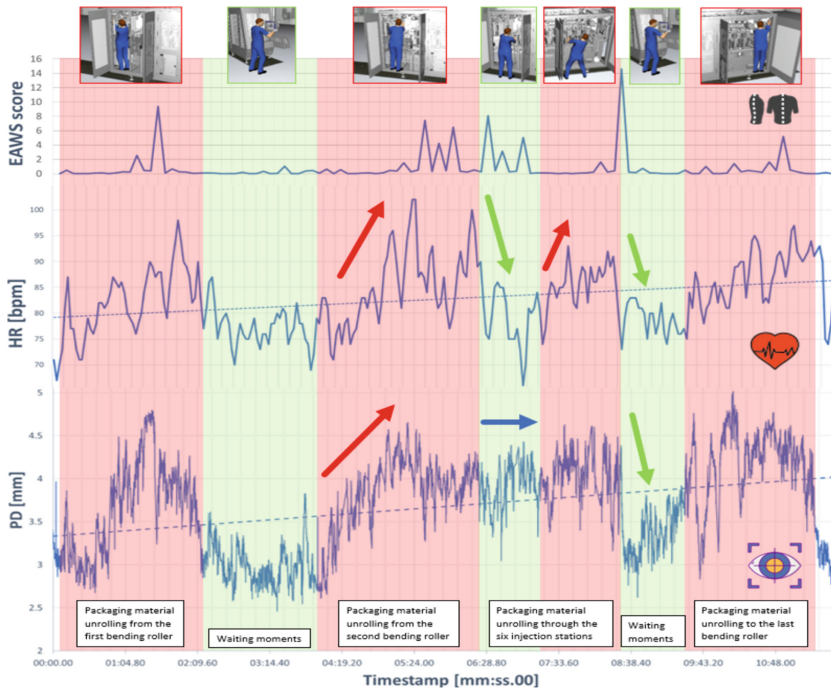


Fig. 2. Results from the post-processing of the operator's physiological data and EAWS score.

6 Conclusions

The paper investigated the application of VM approach to redesign complex systems to enhance the operators' physical and cognitive wellbeing. In particular, the paper proposed a human-centred methodology that drives engineers into a structured design procedure, from the identification of the main redesign goals to the virtual validation using VR tools and motion capture systems. The method is a step forward in the state of

art because it combines the use of human monitoring systems and VR design validation in industry, which is a scarcely investigated topic at the time. The application of the proposed method to a real industrial case study demonstrated its usefulness. The main limitations of the study are mainly related to the complexity of the technological set-up. Future works will address the use of low-cost devices and the further analysis of the physiological parameters, collected during the VR simulation, to provide a more robust evaluation of the mental workload.

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