Design of ergonomic dashboards for tractors and trucks: innovative method and tools

Published Version:
Design of ergonomic dashboards for tractors and trucks: innovative method and tools / Grandi F.; Prati E.; Peruzzini M.; Pellicciari M.; Campanella C. E.. - In: JOURNAL OF INDUSTRIAL INFORMATION INTEGRATION. - ISSN 2452-414X. - ELETTRONICO. - 25:(2022), pp. 100304.1-100304.10. [10.1016/j.jii.2021.100304]

Availability:
This version is available at: https://hdl.handle.net/11585/949356 since: 2024-02-06

Published:
DOI: http://doi.org/10.1016/j.jii.2021.100304

Fabio Grandi, Elisa Prati, Margherita Peruzzini, Marcello Pellicciari, Claudia Elisabetta Campanella, Design of ergonomic dashboards for tractors and trucks: innovative method and tools, Journal of Industrial Information Integration, Volume 25, 2022, 100304, ISSN 2452-414X.

The final published version is available online at:

https://doi.org/10.1016/j.jii.2021.100304

DESIGN OF ERGONOMIC DASHBOARDS FOR TRACTORS AND TRUCKS: INNOVATIVE METHOD and TOOLS

Fabio Grandi[1], Elisa Prati[1], Margherita Peruzzini[1], Marcello Pellicciari2, Claudia Elisabetta Campanella[3]

[1]Department of Engineering Enzo Ferrari, University of Modena and Reggio Emilia, Modena (MO), Italy

[2]Department of Sciences and Methods for Engineering, University of Modena and Reggio Emilia, Reggio Emilia (RE), Italy

[3]CNH Industrial, Ergonomics and HMI, Modena (MO), Italy

Abstract

Designing highly usable and ergonomic dashboards is fundamental to support users in managing and properly setting complex vehicles, like trains, airplanes, trucks and tractors. Contrarily, control dashboards are usually intrusive, full of controls and not really intuitive or usable. This paper focuses on the design of ergonomic and usable dashboard for specific classes of vehicles, like tractors and trucks. Indeed, trucks and tractors are both vehicles and operating machines, and their control is particularly complex. Indeed, the driver contemporary drives and checks if the machine is working properly. The paper proposes an innovative methodology to design highly usable and compact dashboards inspired by human-centered design and ergonomics principles. The study started by shifting the attention from the machine performance, that is the conventional engineering approach, to the human-system interaction quality, according to a new, transdisciplinary approach. The methodology proposes to combine virtual simulations with human performance analysis to support the design at different stages, from concept generation to detailed design, until testing with users. The methodology uses virtual environments to create digital twins of both driver and controls, making users interact with virtual items and predict the type and nature of interaction. Within virtual scenarios, different configurations of dashboard controls can be easily compared and tested, checking the frequency of use of each control and measuring the achieved human performance related to postural comfort and mental workload. The study adopted the proposed methodology to two industrial use cases focusing on the design of ergonomic dashboards: the former is referred to tractor dashboard and armrest, the latter refers to truck dashboard and seat. Both cases demonstrated that the new methodology allowed improved comfort, higher usability, higher visibility and accessibility, better performance and reduced time for machine control. The study demonstrates how a multidisciplinary user information integration can drive design optimization.

Keywords: Virtual simulation, Human-Centered Design, Human Factors, Ergonomics, Usability.

DESIGN OF ERGONOMIC DASHBOARDS FOR TRACTORS AND TRUCKS: INNOVATIVE METHOD and TOOLS

Abstract

Designing highly usable and ergonomic dashboards is fundamental to support users in managing and properly setting demanding vehicles, like trains, airplanes, trucks and tractors. Contrarily, control dashboards are usually intrusive, full of controls and not really intuitive or usable. This paper focuses on the design of ergonomic and usable dashboards for specific classes of vehicles, like tractors and trucks. Indeed, trucks and tractors are both vehicles and operating machines, and their control is particularly complex. Indeed, the driver contemporary drives and checks if the machine is working properly. The paper proposes an innovative methodology to design highly usable and compact dashboards inspired by human-centered design and ergonomics principles. It combines virtual simulations with human performance analysis to support the design at different stages, from concept generation to detailed design, until testing with users, according to a multidisciplinary information integration approach. Within virtual scenarios, different configurations of dashboard controls can be easily compared and tested, checking the frequency of use of each control and measuring the achieved human performance related to postural comfort and mental workload. The study adopted the proposed methodology to two industrial use cases focusing on the design of ergonomic dashboards, demonstrating how the new method and tools allow improving comfort, usability, visibility and accessibility, as well as performance, and reducing time for machine control.

Keywords: Virtual simulation, Human-Centered Design, Human Factors, Ergonomics, Usability.

1. Introduction

Driving and control of tractors and trucks have a lot of common features. They are highly stressful activities, both physically and mentally, which require the driver to continuously multitask for a long time inside the cabin. Moreover, the driver is usually alone, he / she has to drive and contemporarily execute different concurrent tasks on the dashboard, with a lot of pressure for reaching the required quality while assuring safety. The driver has to execute many precise body movements, especially with upper arms, such as steering, looking forward and backward (especially for tractors), while controlling the vehicle's dashboard, using clutch, brake, control levers [1]. Recently, tractors and trucks have been provided with dedicated dashboards, with whom control and execute the operational tasks. Unfortunately, due to the increasing complexity of the work, such dashboards are large and invasive, full of controls and not fully customizable to the users' preferences, as demonstrated by market analysis and panel tests with users. It has been also proved that incorrect posture and behaviors during the use of commands and controls in the long term could generate physical health problems in different upper parts of the body (i.e., arms, neck, shoulders, back, head) [2]. As a consequence, dashboard design plays an important role in defining the driver's comfort and system usability, significantly affecting productivity, comfort and safety [3]. Dashboard design can also include the seat and, in general, the entire vehicle cabin since it determines the reciprocal position of the driver with respect to the interaction devices. In this context, the adoption of an ergonomic design approach is necessary. It supports the inclusion of human factors in the cabin design, with a specific focus on the dashboard controls, in order to respond to physical, psychological, social and cultural needs of human beings [4].

As far as industrial system design, the optimization of posture, physical overload, perceived effort, discomfort, and physical fatigue is fundamental to satisfy the users' needs, prevent musculoskeletal disorders and stressing conditions [5]. In this context, the analysis of human factors has a central role in the understanding of human behaviours and performance interacting with systems, and the application of that understanding to design of interactions [6].
The study started by shifting the attention from the machine performance, that is the conventional engineering approach, to the human-system interaction quality, according to a new, transdisciplinary approach. It presents a methodology integrated with a set of innovative tools to design human-centric, ergonomic dashboard controls and describes their application to real industrial cases, concerning tractor and trucks dashboard design. In particular, the research approach combines different novel tools: on one hand virtual simulation helps to create digital twins of both driver and controls, involving users in preliminary validation and making them interact with virtual items to predict the human-machine interaction during the design process, comparing different design alternatives; on the other hand the acquisition of physical and physiological human parameters gathering the data to assess the real biomechanical performance of users. Such tools are used at the different stages of the design process, according to the proposed methodology. At the beginning, human data monitoring is adopted to study real users acting on existing cabins in order to understand the current ergonomic quality and to define a set of "optical" conditions to achieve. After that, virtual simulation based on fully digital analysis with virtual mannequins can replicate the "typical" user behaviour and easily compare many different configurations of controls, by measuring a global comfort index for each design. When the best design solution is defined, virtual reality (VR) simulation is used to create an immersive, highly realistic, simulation where real users can navigate and test the design at a more detailed stage. During the VR simulation, users can be sensorized by human monitoring tools to collect real time physical and physiological data, in order to objectify the user experience and the perceived comfort.
The paper is organised as follows: section 2 is about the research background, section 3 describes the research approach, the proposed methodology and tools, section 4 presents industrial uses cases for tools validation, when the former is referred to tractor dashboard and armrest, while the latter refers to truck dashboard and seat, and finally section 5 contains conclusions and recommendations for future works.

2. Research background

The goal of ergonomics is not only to improve work performance but also to guarantee human comfort as well as users' safety [4]. If ergonomic aspects are underestimated, system performance will be scarce due to the effect of lower user performance and working time will be higher [7].
Ergonomics is a typically transdisciplinary discipline since it requires technical as well as social-science skills, and certainly involves people from practice. Technical science concerns the design of machines, interfaces and information systems. Social science assists in identifying the needs of users in order to design usable and useful interfaces and interaction systems. The combination of technical and social aspects pushes towards the adoption of a Human-Centered Design (HCD) approach, which pays attention to humans and focuses on the users' needs as the starting point of the design process [8]. HCD allows the development of products and systems able to meet the users' requirements and needs in a timely and effective way. In this context, the quality perceived by users is a key aspect of the design; it can be assessed by considering the overall User eXperience (UX) in the different stages of design [9].
Application of ergonomics to industrial systems is definitely transdisciplinary, as it requires multiple disciplines, as well as people from practice, because the problems encountered can be multi-faceted [10].

The best approach to promote ergonomics in system design is the preventive one, which consists of anticipating ergonomics problems during the design stage in order to optimize the overall system design. Anticipating ergonomics issues means understanding the physiological, psychological, and behavioural capabilities of users, defining users' needs, and translating such needs into design specifications. There are many items acting as stressing factors during the work. These factors may be related not only to physical workload and uncomfortable postures, but also to task complexity, overload of information to be handled, or time pressure [11]. The persistence of stressing factors can cause both physical and mental fatigue, which can be measured in terms of strain on the user, for instance the driver [12].

Numerous methods have been defined in literature to carry out ergonomic assessment with the final scope to detect stressful conditions. Traditional methods mainly focus on physical ergonomics and are based on elaboration of statistical data acquired from previous studies or equations, carried out by expert observation and paper-based checklist. A wide range of assessment techniques and tools exists, focusing on the postures assumed by users during task execution, the managed forces or handled loads, the action frequency, and so on. A detailed review has been provided by [13]. Among these tools, the most adopted are listed hereafter. NIOSH lifting equation is able to determine the so-called recommended limit weight for each operator and is particularly indicated when a worker has to repeatedly handle heavy loads during his shift. In manufacturing context, OWAS method (Ovako Working posture Assessment System) [14] is used to carry out a preliminary ergonomic assessment evaluating the position assumed by back, arms and legs and the transported load. Other methods apply the same approach but consider a more detailed evaluation of the human segment's position, such as RULA (Rapid Upper Limb Assessment) [15] and REBA (Rapid Entire Body Assessment) [16]. Concerning the comfort evaluation in vehicles, Dreyfuss 3D [17] provides optimal ranges for human body joints in order to guarantee high standards of wellbeing during driving tasks. For the specific case, the expert has to select the proper methods to analyze the current conditions. However, these tools are not preventive, but rather consumptive [18].

A preventive approach can be implemented only if the working conditions are predicted in advance, during the design stages, using desktop-based digital human simulation (DHS). It uses virtual human simulation, replicating the user actions by digital mannequins, to carry out ergonomics analysis within virtual environments, based on human anthropometric information [19]. Various commercial systems are available for ergonomic analysis of human posture at work. This approach offers a virtual user in a simulated working environment and effectively supports the identification of the main ergonomic issues, in particular reachability, clearance, and visibility. Such assessment is rapid and effective to be used during the preliminary design stages, but not accurate. Indeed, analyses provide a static "picture" of the tasks, without considering the dynamic aspects of human actions. Moreover, such tools are limited in case of awkward postures and do not consider the effect of high-frequency or heavy handled loads [20]. Despite these limitations, digital human simulation helps the detection of static postures and exceptional strains in a more secure and fast way than in real-life assessments.

In order to better match the digital simulations with real users' behaviours, VR technologies can help to involve users in a realistic scenario. VR allows creating immersive, interactive environments where task execution can be simulated with a higher level of realism thanks to a three-dimensional stereoscopic view and motion capture systems able to collect the movements of real users in order to update the simulation coherently. By tracking the user movements, a real time postural analysis on a continuous flow of actions, closer to real activities, can be carried out. Two main approaches are today widely recognized: real time motion capture and video analysis [21]. A lot of research demonstrates that VR simulations well support users to better analyze the users' needs in different contexts and to create an enhanced interaction framework to understand the human-machine interaction [22]. The main benefits linked to the adoption of VR technologies consist of anticipating potential issues and design changes and having precise feedback about human-machine interaction before the product launch. This means a shortened time to market, faster product design reviews, as well as an improved product quality and an enhanced workers' satisfaction and safety [23].

However, such methods mainly focus on physical assessment. Contrarily, user interfaces and dashboard require to synergically consider both physical and mental workload to find an optimum by designing the best solution. In this direction, the use of physiological measures could be useful to detect the state of users' stress in an objective way [24, 25].

The most common analyses to detect stressful conditions typically include electrocardiography (for heart rate monitoring), electromyography (for monitoring muscles activity through their electrical potentials), the pneumography (for respiration control) or the skin conductivity (to measure sweat activity) [26, 27]. However, the multimodal dimension of stress makes the research field very broad. Four criteria can be distinguished in detecting human stress, according to ISO 10075-3 [28]: psychological, physiological, behavioural, and biochemical. They are also strictly interconnected and highly dependent on each other. In general, stressful actions can be detected by multiple ways: for instance, at a physiological level the increase of nervous system activity changes hormone levels in the body and provokes reactions such as sweat production, increased heart rate, and muscle activation. Breathing rate (BR) becomes faster and increases blood pressure. Usually, skin temperature and heart rate variability fall. The diameter of the pupils can vary. Finally, behavioural reactions include eye movements and eye change rates, as well as changes in facial appearance and head movements.

There are many physiological signals to be used in stress detection and some of them have shown to provide reliable information about peoples' real-time stress levels [29]. Electrocardiogram (ECG) is one of the most used signals in stress detection research because it directly reflects the activity of the heart, mainly the Heart Rate (HR, defined as the number of heart beats per minute), the Heart Rate Variability (HRV, defined as the temporal variation between sequences of consecutive heart beats) and the LF/HF ratio (low frequency / high frequency). Generally, the increase of the HR and the decrease in the HRV can reveal an increased level of mental effort during the execution of a task [30].

Moreover, eye activity in terms of number of gazes and blink rates can be measured with infrared eye tracking systems or with image processing techniques applied to visual spectrum images of the eyes. Thus, pupil dilation usually exhibits changes under stress situations and can be measured by the dilation mean value, standard deviation, gaze spatial distribution, number of fixations, as well as the blink rate or blinking frequency. Other useful tools for investigating the visual path of users are heat maps and gaze plot: the former provides information about the gaze distribution over an area, the latter is a map which shows gaze fixations and the order in which they occur. The analysis of these maps could be effectively applied in different phases of the design cycle to understand how a dashboard, or an interface, is perceived by users [31].

3. Research methodology

The research approach integrates VR simulation with different tools for the acquisition of physical and physiological parameters in order to support system design or redesign by objectifying the users' experience and workload. The research methodology is structured in three phases detailed as follows.

Phase 1 – User driving in the real environment. First of all, real users are monitored during field tests in the real environment, while interacting with the real, physical dashboard. The human monitoring sensors as well as the seat pressure sensors are used. Users are asked to carry out representative tasks (e.g., the most frequent and the most characteristic ones) depending on the specific context of use. During this phase, a sample of users drives a real tractor or truck, executing a set of predefined activities. In the meanwhile, physiological and physical data are collected by wearable technologies, such as biosensors and eye-tracking glasses. The selected sample of users has to be representative of the target users of the specific product under investigation. The goal is to define the typical users' actions and to identify the main critical tasks and the main interaction difficulties. This phase allows to analyze how commands and controls are used, highlight ergonomic issues and propose a more usable grouping as guidelines for new dashboard design. This phase can be organized in the following sub-phases:

1. Task selection;
2. Monitoring tools selection and set-up (e.g. biosensors, eye-tracker, pressure mapping system, external cameras, telemetry system);
3. Task execution in the real context;
4. Physiological data collection;
5. Data analysis and post-processing.

From biosensors, data related to HR and HRV can be graphed in time domain in order to understand their correlation with stressful situations, according to [29]. At the same time, the telemetry system allows to track the user commands' activation along the time; such information can be overlapped with the HR and HRV graphs to understand the level of mental effort connected to the use of a specific command or during the execution of a certain task. Contemporarily, eye data analysis from eye-tracking helps to visualize the visual interaction with the entire dashboard and carry out detailed visibility analysis, extracting heat maps and gaze plots. Finally, the pressure mapping system collects seat pressure data and produces pressure maps able to define the level of physical comfort.

The results obtained from this first step can highlight the main criticalities during the human-machine interaction and drive the definition of the necessary redesign actions. However, we need to know in advance the effect of any possible changes and simulate different design alternatives to understand the best one to further develop.

Phase 2 – Digital Human Simulation. This phase adds the power of virtual simulation to the previous analysis. Indeed, on the basis of data collected during Phase 1, different dashboard designs can be conceived and prototyped digitally. Digital simulation using virtual mannequins allows identifying the macroscopic usability, ergonomic, visibility and reachability issues and understanding how to solve them. Virtual mannequins are generated according to data collected in Phase 1 to model the behaviour of target users. Mannequins can easily represent different-sized operators, using different percentiles of the selected population (e.g., 5th, 50th, 95th), and for each of them they allow checking visibility, reachability and joint comfort on different dashboard proposals, according to specific ergonomic metrics (e.g., Dreyfuss 3D). Different cabin layouts and dashboards design can be easily compared in this way. This phase can be organized in the following sub-phases:

1. Generation of dashboard redesign solutions
2. Virtual mannequins' definition
3. Digital human simulation on different digital solutions
4. Comfort, visibility, and reachability assessment, using standardize ergonomic methods

Different ergonomic tools can be adopted during the digital human simulation, according to the type of tasks executed. If users are seated, like in the majority of control dashboards within a vehicle, Dreyfuss 3D and RULA can be adopted to extract comfort angles from the virtual mannequins and compare them with suggested values. Moreover, view cones can be visualized on the virtual space to understand the users' field of view, considering the different percentiles, and to assess the dashboard visibility along the task execution. Similarly, reach zones can be visualized as spheres all around the mannequins' arms to understand the available reach areas.

This phase helps designers to identify the best design solution to be further developed and prototyped, having tests with users.

Phase 3 – Users interacting in the new virtual cabin. The next step is creating a VR interacting simulation environment and organizing testing sessions in Lab involving real users to finally validate the most promising solution, based on results from Phase 2. A proper VR engine platform is used to create interactive environments. A motion capture system allows tracking the real users' movements during virtual testing while a hand tracking system can make users interact with the virtual dashboard. VR immersive simulation is useful to evaluate the physical interaction with the final dashboard layout and to validate the perceived quality by user-based assessment. Interaction is better analyzed by using the human monitoring devices also adopted in Phase 1, such as: eye tracker, seat pressure mapping system, biosensors, external cameras. Thanks to digitized users, the joint angles and comfort indexes can be calculated according to the most proper ergonomic methods. This phase can be organized in the following sub-phases:

1. Creation of the VR simulation;
2. Virtual testing sessions;
3. Human data collection;
4. Data analysis and post-processing.

Motion capture is used to track and record the users' movements and to carry out physical ergonomic assessment using the same methods as adopted in Phase 2 (e.g. Dreyfuss 3D and RULA). Similarly, to Phase 1, biosensors data related to HR and HRV are used to detect the users' physiological status and find correlations with stressful situations. Contemporarily, eye data analysis from VR eye-tracking helps to visualize the visual interaction into the virtual scene and carry out detailed visibility analysis, extracting heat maps and gaze plots. Finally, the pressure mapping system collects seat pressure data and produces users' seat pressure maps to add useful information to the physical comfort assessment.

Phase 3 provides a final validation of the selected redesign solution having a direct feedback from users involved in the virtual simulation, before producing a physical prototype. Fig.1 shows the proposed methodology and the adopted tools for each phase, for the specific context of application.

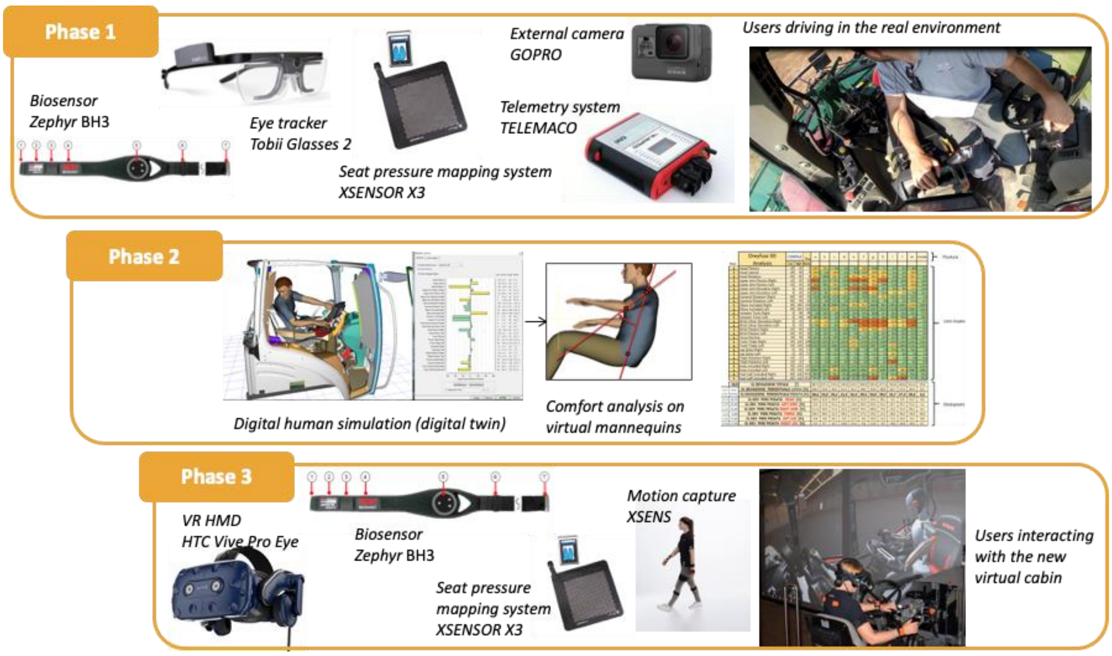

Fig. 1. The 3-phase methodology and the adopted tools

The adopted tools, in the three above-mentioned phases, are as follows:

- Sensors for real-time analyses of the main physiological parameters of the users, which can provide clear feedback on the driver's state without interference with the driver's activities. The adopted sensors refer to: a biosensor for electrocardiography (for HR and HRV data recording), breathing monitoring (for BR analysis) (i.e., BH3 by Zephyr) and an eye-tracking device for eyes' fixation analysis and visual attention mapping (i.e., Pro Glasses 2 by Tobii);
- Seat pressure sensors to collect pressure data on the seat during driving and task execution (i.e., Xsensor X3);
- Motion capture for real-time analyses of body movements, to measure the position of the different body parts (e.g., arms, hands, head) and to objectify the human interaction in terms of distance, joint angles, instantaneous speed or acceleration) (i.e., Xsens MVN by Xsens);
- Human simulation software for virtualization of human-machine interaction and physical ergonomic analysis by Dreyfuss methods (i.e., Jack by Siemens);
- Telemetry system for vehicle data collection to analyze the human interaction (i.e., CAN (Controller Area Network) system) to check whether and what type of interaction is taking place during task execution;
- A VR engine platform (i.e., Unity 3D) to create interactive, highly realistic simulations of dashboards to test directly in the virtual environment by involving users, emulate human-machine interaction;
- A VR Head-Mounted Display (HTC VIVE Pro Eye) to make users live the virtual simulation as created by the VR engine platform. The Pro Eye model also integrates the eye tracking to follow the visual interaction and pupil diameter also during virtual simulation.

Fig. 2 represents the proposed data elaboration framework, where all sensors are included.

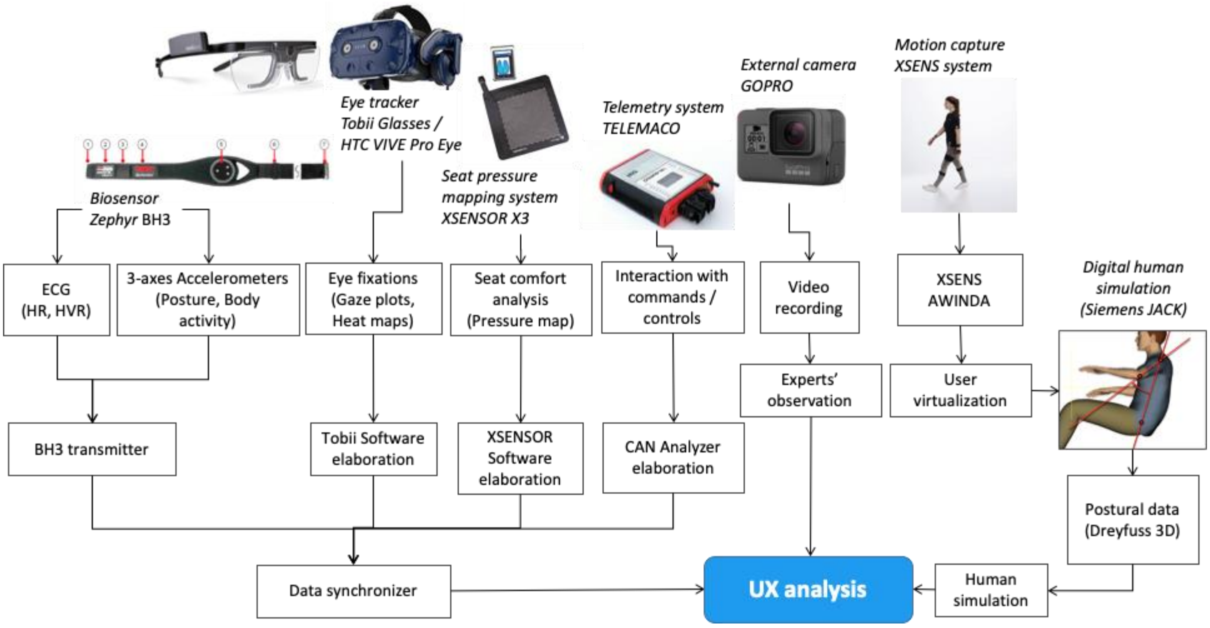

Fig. 2. The proposed data elaboration framework

4. Experimental testing

Experimental study focuses on two use cases developed in collaboration with CNH Industrial, a global leader company producing agricultural machines, trucks and buses. The first use case (UC1) focused on tractors from the Steyr brand, in particular on the design of the new Expert CVT dashboard controls.

The second use case (UC2) focused on trucks from the Iveco brand, in particular on the design of the new Stralis S Way cabin. Both products are aimed at customers who need high performance vehicles with compact dimensions and high comfort. Both use cases were developed according to the proposed methodology to improve the ergonomics of the cabin, with a particular attention to physical comfort and usability, as described in the following paragraphs.

4.1. Tractor use case (UC1)

The selected Stayer tractor model is characterized by a particular ergonomic attention and a multi-controller armrest able to merge comfort, flexibility and high-quality performance. Indeed, its cabin is characterized by smaller dimensions (minor length and width with respect to other Steyr models), lower intrusiveness for the operator trunk-legs, and improved sensation of roominess inside the cabin. The methodology was applied to define the features to create the expected characteristics with the final aim at improving the human comfort during working in a tractor cabin and reduce the mental workload. During Phase 1, five target real users were selected and involved in on-field testing driving the as-is tractor model. Users involved belong to the product “target”, so they are well-experienced, professional drivers and get use to drive tractors like this one in similar operating environments. In this specific case, the attention was focused on expert drivers, and did not make sense to have a comparison with novice users. Users were asked to carry out the most common tasks driving the real tractor and their actions were tracked to map the users’ behaviours and needs, thanks to the proposed set-up, as shown in Fig.3. The picture on the left describes the main controls of the cabin under investigation, while picture on the right shows how users are equipped to carry out the human behavior analysis, including the eye tracking glasses (2), the telemetry data recording unit (4), the external camera for videorecording (5) and the biosensor (6).
After the data collection phase, all data were synchronized and post-processed to obtain a relation between the task sequence, the physiological data, and the activation of specific controls in the cabin. Fig.4 shows how such data can be related and interpreted for a specific mission chuck (i.e., using the power harrow with a seeder). Such data analysis was performed on 18 different missions, from plowing to snow shovel.

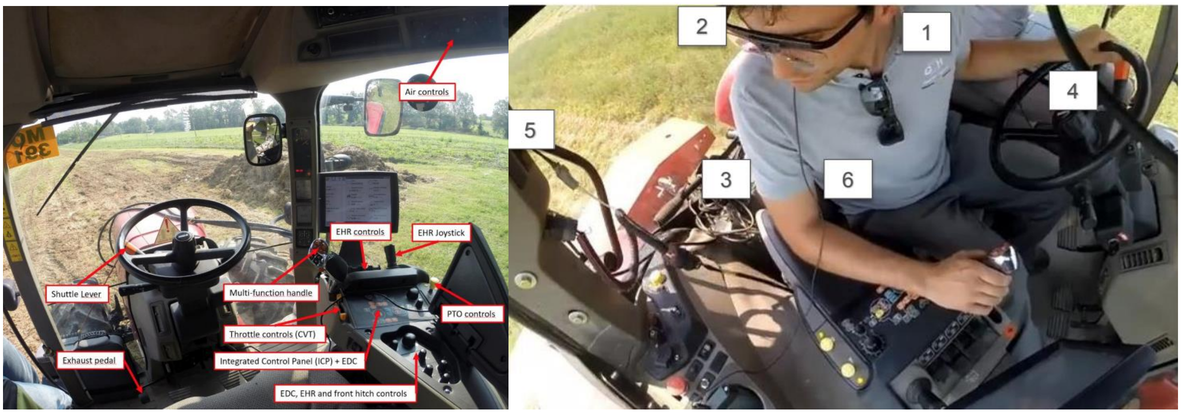

Fig. 3. UC1 Phase 1: real tractor used for testing (left) and users monitored by the proposed set-up (right) - 1 driver, 2 eye tracking glasses, 3 data storage unit, 4 CAN data recording, 5 GoPro camera, 6 biosensor

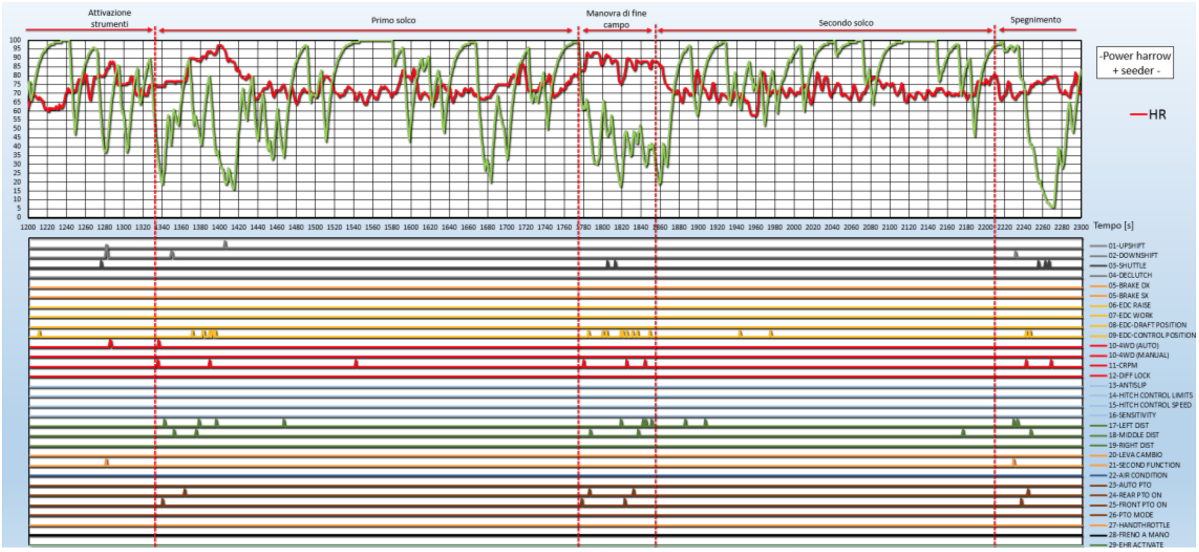

Fig. 4. UC1 Phase 1: physiological human data (top) related to the control activation (bottom) for a specific user during field tests

Phase 2 was oriented to create reliable virtual mannequins belonging to different percentiles (5p, 50p and 95p) to represent different-sized operators. Many proposals were investigated, to find out the good compromise between reduced dimension of the armrest and a visible and effective control layout to be operated in comfort for different human percentiles. Fig. 5 shows the virtual prototype of the designed armrest and examples of virtual tests with digital mannequins belonging to different percentiles (5p, 50p and 95p) to test reachability and visibility. After that, a new armrest was designed to improve the user comfort and the overall system usability.

Finally, Phase 3 focused on the VR simulation in the company Virtual Lab involving 5 users (different from users involved in Phase 1), to check the quality of an improved armrest for the Steyr tractor under investigation. This phase aimed to measure the quality of interaction and the achieved performance. During the simulation, users were asked to carry out a set of tasks, randomly selected from the 18 analyzed missions. Fig. 6 shows the new armrest layout and immersive testing on the system mock-up.

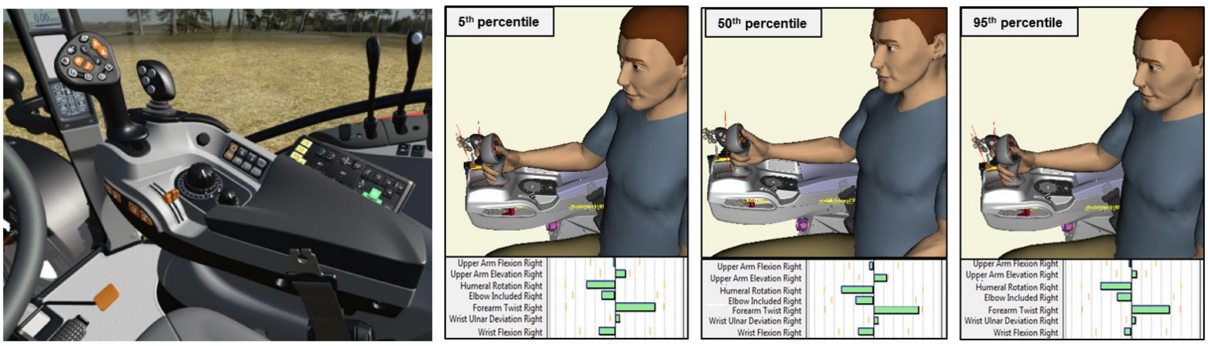

Fig. 5. UC1 Phase 2: virtual prototype of tractor armrest (left) and virtual tests on different percentiles (right)

Fig. 6. UC1 Phase 3. Immersive VR test in Lab of the new armrest layout based on intuitive-grouped control panel

4.2. Truck use case (UC2)

The dashboard of the selected Iveco model is characterized by low intrusiveness for the operators' trunk-legs and an improved sensation of roominess inside the cabin. Moreover, it has an innovative controls layout, with many controls managed with pushbuttons, grouped in a more organized-intuitive way using different panels to help operators to immediately find each control.

During Phase 1, five users were monitored during tests on the as-is truck model using the proposed set-up, to define the typical users' actions and to identify the main critical tasks and the main interaction difficulties. In this phase, users were expert in driving tractors, but with a different level of familiarity with VR technologies in order to monitor the eventual impact of the technology on the achieved performances. As in UC1, the attention was focused on expert drivers, and did not make sense to have a comparison with users with no experience in tractor driving.

Contemporarily, a benchmarking on seat shape was developed, basing on pressure maps. During this phase, users drove the real truck and their physical data were collected by the motion capture system and the seat pressure sensors, while video-recorded data were collected from the truck itself as shown in Fig.7. This phase allowed to define the users' behaviours and needs and to analyze how commands and seats are commonly used, to propose an ergonomic grouping for the new dashboard design and to create a seat comfort pressure map benchmarking.

Fig. 7. UC2 Phase 1: real users monitored by the proposed set-up on a real truck cabin - 1 driver, 2 eye tracking glasses, 3 seat pressure sensors, 4 CAN data recording, 5 GoPro camera, 6 motion capture system

During Phase 2, users were virtualized to create target digital twins. Different cabin layouts can be simulated and verified on the basis of virtual mannequins, belonging to different percentiles (5p, 50p and 95p) to represent different-sized operators. For each of them, visibility, reachability, and comfort of the human joints were verified by comparing different cabin proposals as shown in Fig. 8. Many proposals were investigated, especially to find out the good compromise between a visible and effective control layout to be operated in comfort for different human percentiles. For each proposal and for each percentile, a comfort index has been computed related to both arm comfort (elbow-wrist angles) and leg comfort (ankle- knee-hip angles).
Finally, Phase 3 considered the VR immersive simulation, involving five users (also in this case, different from those involved in Phase 1). The motion capture system was used to track the users' movements within the virtual environment and emulate the human-machine interaction, for a realistic VR simulation. This simulation was useful to evaluate design alternatives and validate the final dashboard layout. Moreover, motion capture allowed creating more reliable digital twins of real users, and to effectively measure the joint angles and comfort indexes, simulating real missions. Fig. 9 shows the new control layout based on an intuitive-grouped control panel and an example of an immersive VR test in Lab. Fig. 10 shows the pressure maps for different seat typologies (backrest on the left, cushion on the right).

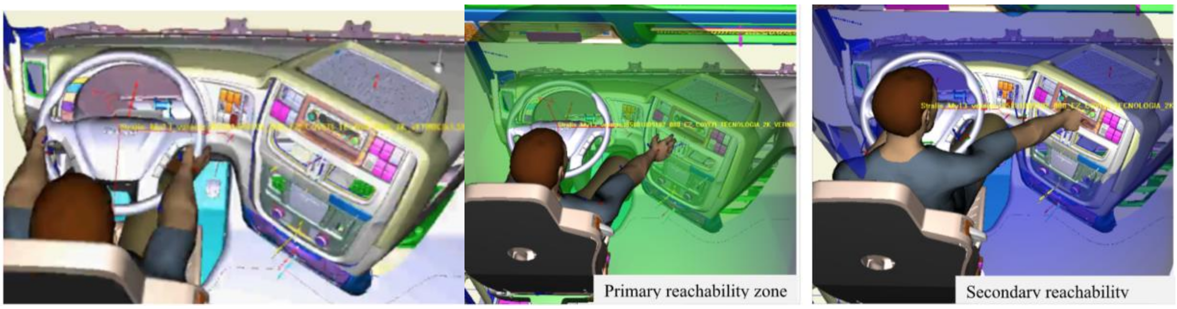

Fig. 8. UC2 Phase 2: virtual prototype of the truck cabin (left) and virtual tests for reachability (right)

Fig. 9. UC2 Phase 3: new control layout based on intuitive-grouped control panel (left) and immersive VR test in Lab (right)

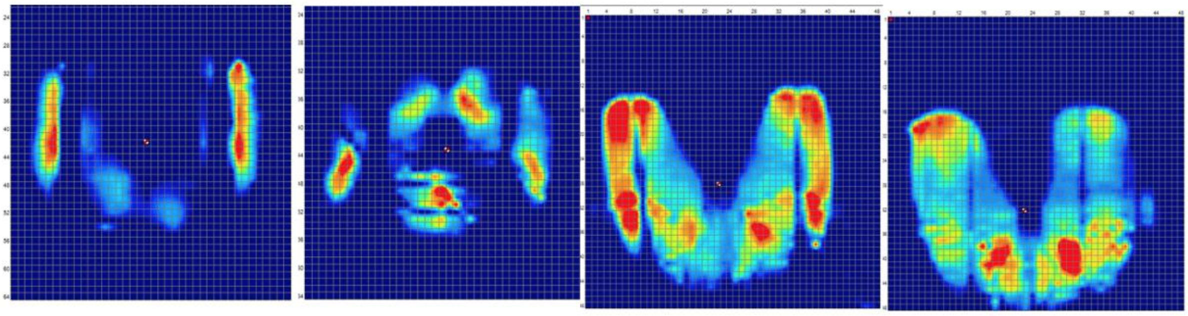

Fig. 10. UC2 Phase 3: seat pressure data on different seat (backrest on the left, cushion on the right)

4.3. Results and discussion

The use cases were useful to validate the proposed methodology and to understand whether human monitoring can effectively add helpful information to drive new design actions. Both cases allowed us to monitor the user's physiological and physical data and correlate them with the interface use and visual interaction data. Moreover, they also demonstrated the possibility to analyze the user workload in order to understand the level of comfort and usability of the dashboard, considering also the level of stress and the perceived quality of interaction. UC1 mainly focused on the control grouping on the new armrest design, while UC2 focuses on improving the relation between the seat and the dashboard, including also the seat comfort in the global comfort of the cabin design. The main advantages of the proposed approach are the adoption of the users' reliable digital twins during the design phases, in order to validate different design solutions involving users, thanks to the understanding of the real users' behaviour, and the improved VR simulations thanks to the preliminary but strategically important design review on digital mock-ups.

Compared to traditional HCD approaches, mainly based on subjective impressions of users using questionnaires, the proposed method proposes an evolution of the UX analysis based on objective, measurable data, from motion capture and physiological data analysis. Compared to traditional DHS approaches using only virtual mannequins, the proposed methodology is more robust and objective by merging a first-round of selection of design alternatives using desktop-based simulation on avatars with a second-round of analysis based on testing with real users. With respect to traditional ergonomic assessment, based on video analysis and checklist, the proposed method is faster and more efficient thanks to virtual simulation, and can offer a more detailed analysis thanks to the physiological data analysis, considering also the perceived UX and generated stress conditions. Indeed, traditional assessment is based on a time-consuming video recording analysis from ergonomics experts, reconstruction of postural angles, manual calculation of the selected tools, and a subjective definition of design changes. This phase usually requires a certain effort, depending on the project complexity (e.g., from 1 to 3 months in general). Moreover, the design changes are defined thanks to the personal experience of the expert, and need to be validated on the field, when the next product is at least prototyped physically. Virtual analysis with mannequins can fasten and objectify the ergonomic assessment, reducing time (e.g., 2-3 weeks in general) and limiting the subjective impact of the evaluation. Finally, the use of the VR prototype to have a preliminary assessment of the new cabin with real users allow to anticipate the feedback on the new solutions, without waiting until the new product is physically prototyped or even produced.

Thanks to the research use cases, the advantages related to the proposed approach were found to sensibly reduce the time to market with respect to a fully digital-based approach (only Phase 2). The multi-level approach combined digital simulation with human data to create more effective digital environments where users can interact in advance with the product features, to address the main interaction criticalities during the design stage. Moreover, the predictive analysis can be carried out before the real product realization, and an optimized product will be created, avoiding also late optimization actions. Finally, the use of VR simulations allows easily testing the most promising product layouts, replicating the sequence of actions, predicting the user movements, and defining the best design solution.

The main results obtained from UC1 are:

- Higher comfort index for all users, and in particular for taller users (95p) as demonstrated by the maps' toolkit. Fig. 11 highlights how 5p, 50p and 95p users can comfortably accommodate in the new armrest cushion, using all armrest possible adjustments (all green boxes, higher than 75%);
- Reduced encumbrance as the new armrest is 20% shorter and 30% thinner than the previous one). Fig. 12 shows the main dimensions of the new armrest and compared it with the previous armrest;
- Higher performance and reduced time for tractor control due to an optimized control layout with push button panels.

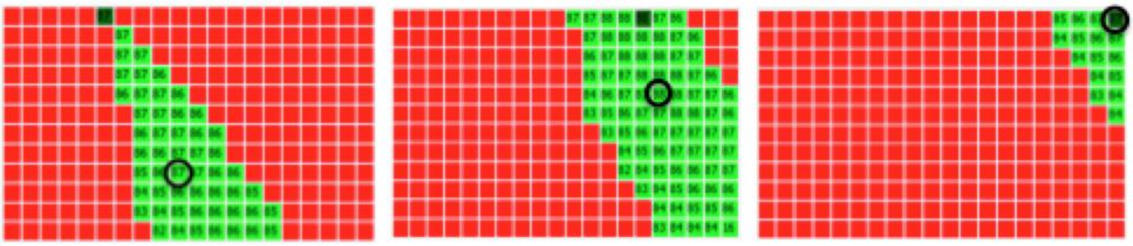

Fig. 11. UC1 comfort result: comfort maps for the new dashboard design (5p, 50p, 95p)

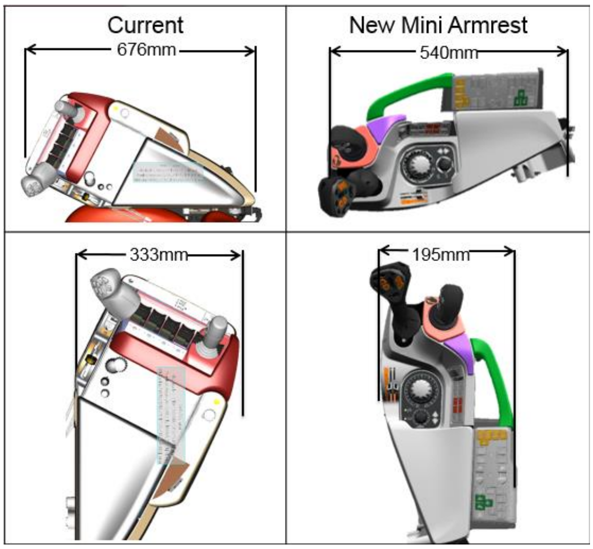

Fig. 12. UC1 compactness result: dimension comparison between the previous armrest and new compact-ergonomic armrest

The main results obtained from UC2 are:

- Higher comfort index for all users, and in particular for taller users (50p) as demonstrated by the software maps toolkit. Fig. 13 shows comfort maps and highlights how 5p, 50p and 95p mannequins can comfortably accommodate in the new seat-dashboard workspace, using all possible seat adjustments (all green boxes are higher than 87%);

- Higher performance and reduced time for truck control due to an optimized control layout with push button panels (indeed, the new dashboard allows keeping on board only frequent controls positioned in an ergonomic way).

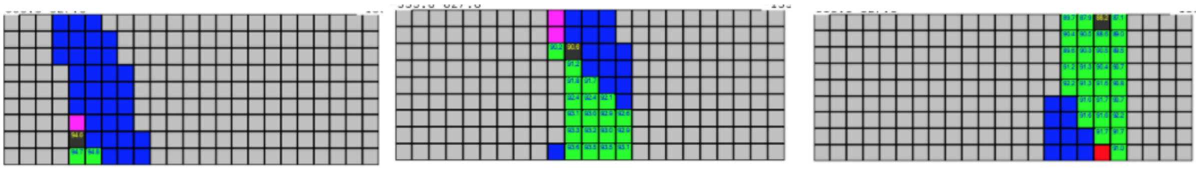

Fig. 13. UC2 comfort result: comfort maps for the new dashboard design (5p, 50p, 95p)

5. Conclusions

This paper presented a set of innovative tools and a human-centered methodology to promote human factors and ergonomics in the design of industrial systems- In particular, they were applied to the design of usable, human-centered control dashboards of tractors and trucks. The paper described the methodology and tool application to two industrial use cases, developed in collaboration with CNH Industrial. The new approach combines digital technologies, VR and human monitoring devices to assess the real user experience and to introduce ergonomics validation during the cabin design stage, before product realization, with the final aim to improve the product quality and consumer satisfaction as well as to reduce time to market. Indeed, the new approach allowed not only to better satisfy the user's needs and to improve the user comfort as well as dashboard usability, but also to reduce the design time, reducing also the final product costs. In particular, about the tractor case, the new armrest was smaller than the previous one (-30% in dimensions) and usable (keeping on board only frequent controls, better positioned). Similarly, about the track case, the dashboard was more compact and usable. Both solutions were found more comfortable (they satisfied 95% of the population size). Such results could be used also to guide the new design for other tractor or truck controls and dashboards, so that human comfort can be optimized and any task can be felt as natural as possible, encouraging good posture and safe behaviours, and reducing cost of prototypes and time to market. From a societal viewpoint, the inclusion of human factors in systems design can overcome the current issues due to changes in technologies and requirements of workers and enhance their work conditions. The proposed methodology merges different disciplines in order to assess the general comfort of the user, according to a transdisciplinary approach.

Future works could be addressed to improve the proposed methodology and extend its applicability. In phase 1 and phase 3, less intrusive devices for human data monitoring could be used to reduce the intrusiveness and make users feel more relaxed during the testing; for instance, using modern smartwatches or bracelets to record physiological human data, replacing the chest belt that need to be moistened and worn under clothing. In phase 3, the Xsens motion capture system could be replaced by different systems, less sensitive to interferences and less expensive; this fact will support the extension also to other contexts like industry to support the design of new machines, where interference problems usually occur at the shop floor and attention to cost is higher than in automotive design.

The proposed method could finally be adapted to other contexts by properly setting devices and monitoring environments, to design any type of systems that require a close user interaction, from industrial machinery, to military equipment, to medical equipment.

Acknowledgement

The authors wish to acknowledge CNH Industrial staff for the precious collaboration.

References

[1] Bashiri, B., Mann, D.D., Automation and the situation awareness of drivers in agricultural semi-autonomous vehicles. *Biosystems Engineering*, vol. 124, 2014, pp. 8-15.
[2] Metha, C.R., Tewari,. V.K., Seating discomfort for tractor operators - A critical review, *International Journal of Industrial Ergonomics*, vol. 25(6), 2000, pp. 661-674.
[3] Hsiao, H., Whitestone, J., Bradtmiller, B., Whisler, R., Zwiener, J., Lafferty, C., Kau, T.Y., Gross, M., Anthropometric criteria for the design of tractor cabs and protection frames, *Ergonomics*, vol. 48 (4), 2005, pp. 323-353.
[4] Ergonomics of human system interaction - Part 210: Human-centered design for interactive systems, International Organization for Standardization (ISO), ISO 9241-210, 2009.
[5] Pheasant, S., Body Space: Anthropometry, Ergonomics and the Design of Work, Taylor & Francis, Philadelphia, pp. 121-123, 1999.
[6] Wilson, J.R., Fundamentals of ergonomics in theory and practice, *Applied Ergonomics*, vol. 31, 2000, pp. 557-567.
[7] Norman, D. A., The design of everyday things. New York: Doubleday, 1990.
[8] Norman, D. A., Human-centered design considered harmful, *Interactions*, vol. 12(4), 2005, pp. 14-19.
[9] Robert, J. M., Lesage, A., Designing and evaluating user experience. In The handbook of human-machine interaction, CRC Press, 2019, pp. 321-338.
[10] Wognum, N., Bil, C., Elgh, F., Peruzzini, M., Stjepandić, J., Transdisciplinary systems engineering: implications, challenges and research agenda, *Int. J. Agile Systems and Management*, vol. 12 (1), 2019, pp. 58-89.
[11] Zhang, J.Y., Qiu, W.W., Fu, H.J., Zhang, M.T., Ma, Q.G., Review of techniques for driver fatigue detection, *Applied Mechanics and Materials*, vols. 433-435, 2013, pp. 928-931.
[12] Peruzzini M., Grandi F., Pellicciari M., Campanella C.E., User Experience Analysis Based on Physiological Data Monitoring and Mixed Prototyping to Support Human-Centred Product Design. In: Rebelo F., Soares M. (eds) Advances in Intelligent Systems and Computing, vol. 77, 2019, pp. 401-412.
[13] Joshi, M., Deshpande, V., A systematic review of comparative studies on ergonomic assessment techniques. International Journal of Industrial Ergonomics, vol. 74, 2019, no. 102865.
[14] Karhu, O., Kansi, P., Kuorinka, I., Correcting working postures in industry: a practical method for analysis, *Applied ergonomics*, vol. 8(4), 1977, pp. 199-201.
[15] McAtamney, L., Corlett, N.E., RULA: A Survey Method for the Investigation of Work-Related Upper Limb Disorders, *Applied Ergonomics*, vol. 24 (2), 1993, pp. 91–99.
[16] Hignett, S., McAtamney, L., Rapid entire body assessment (REBA), *Applied ergonomics*, vol. 31(2), 2000, pp. 201-205.
[17] Dreyfuss, H., Henry Dreyfuss Associates, & Tilley, A. R., The measure of man and woman: human factors in design. Whitney Library of Design, 1993.
[18] Takala, E. P., Pehkonen, I., Forsman, M., Hansson, G. Å., Mathiassen, S. E., Neumann, Sjøgaard, G., Veiersted, K.B., Westgaard, R.H. and Winkel, J., Systematic evaluation of observational methods assessing biomechanical exposures at work. *Scandinavian journal of work, environment & health*, 2010, pp. 3-24.

[19] Hou, H., Sun, S. and Pan, Y., “Research on virtual human in ergonomics simulation” *Chinese Journal of Mechanical Engineering (English Edition)*, vol. 13, 2000, pp. 112-117.

[20] Feyen, R., Liu, Y., Chaffin, D., Jimmerson, G. and Joseph, B., “Computer-aided ergonomics: A case study of incorporating ergonomics analyses into workplace design,” *Applied Ergonomics*, vol. 31 (3), 2000, pp. 291–300.

[21] Mavrikios, D., Karabatsou, V., Alexopoulos, K., Pappas, M., Gogos, P., & Chryssolouris, G., An approach to human motion analysis and modelling. *International Journal of Industrial Ergonomics*, vol. 36 (11), 2006, pp. 979-989.

[22] Ke, S., Xiang, F., Zhang, Z., & Zuo, Y., A enhanced interaction framework based on VR, AR and MR in digital twin. *Procedia CIRP*, vol. 83, 2019, pp. 753-758.

[23] Grandi, F., Zanni, L., Peruzzini, M., Pellicciari, M., Campanella, C. E., A transdisciplinary digital approach for tractor’s human-centred design, *International Journal of Computer Integrated Manufacturing*, vol. 33(4), 2020, pp. 377-397.

[24] Peruzzini, M., Tonietti, M. Iani, C., Transdisciplinary design approach based on driver's workload monitoring. *Journal of Industrial Information Integration*, vol. 15, 2019, pp. 91-102.

[25] Aricò, P., Borghini, G., Di Flumeri, G., Bonelli, S., Golfetti, A., Graziani, I., Pozzi, S., Imbert, J-P., Granger, G., Benhacene, R. & Schäfer, D., Human factors and neurophysiological metrics in air traffic control: a critical review. *IEEE reviews in biomedical engineering*, vol. 10, 2017, pp. 250-263.

[26] Boubaker, K., Colantoni, A., Allegrini, E., Longo, L., Di Giacinto, S., Monarca, D., A model for musculoskeletal disorder-related fatigue in upper limb manipulation during industrial vegetables sorting, *International Journal of Industrial Ergonomics*, vol. 44, 2014, pp. 601-605.

[27] Healey, J.A., Picard, R.W., Detecting Stress During Real-World Driving Tasks Using Physiological Sensors, *IEEE Transactions on intelligent transportation systems*, vol. 6, 2005, pp. 156-166.

[28] Ergonomic principles related to mental workload — Part 3: Principles and requirements concerning methods for measuring and assessing mental workload, International Organization for Standardization (ISO), ISO 10075-3, 2005.

[29] Alberdi, A., Aztiria, A., Basarab, A., Towards an automatic early stress recognition system for office environments based on multimodal measurements: A review, *Journal of Biomedical Informatics*, vol. 59, 2016, pp. 49-75.

[30] Sharma, N., Gedeon, T. Objective measures, sensors and computational techniques for stress recognition and classification: A survey. *Computer methods and programs in biomedicine*, vol. 108(3), 2012, pp. 1287-1301.

[31] Prati, E., Grandi, F., Peruzzini, M., Usability Testing on Tractor’s HMI: A Study Protocol. In International Conference on Human-Computer Interaction, Springer, Cham., 2021, pp. 294-31.

Credit Author Statement

Fabio Grandi: Data curation, Writing - Original draft preparation
Elisa Prati: Software, Validation
Margherita Peruzzini: Conceptualization, Methodology, Reviewing
Claudia Elisabetta Campanella: Software, Validation
Marcello Pellicciari: Supervision

Reviewer #1:

In general, the authors responded to the remarks and expectations formulated during the first review.

The bibliography has been completed and the methodology is more detailed.

Some minor remarks:

- Choose as keyword Human-Centered Design more than User-Centered Design

Done

- Name the 3 phases of the methodology. It is easier to memorize / understand a methodology when the phases have names.

Done, the three phases have been titled:

Phase 1 - Users driving in the real environment

Phase 2 - Digital human simulation

Phase 3 - Users interacting with the new virtual cabin

- In the conclusion section, give prospects for work to improve the methodology or adapt it to other contexts.

Done, changes are tracked in red color in the revised version.

- Check all bibliographic references (for example, the date 2017 is missing in reference [9]).

Done. All references have been checked.

- Reference to the following article could be made:

Joshi, M., & Deshpande, V. (2019). A systematic review of comparative studies on ergonomic assessment techniques. International Journal of Industrial Ergonomics, 74, 102865.

It has been inserted in Section 2 in the Research Background, as reference no. 13. Other references have been updated consequentely.

Reviewer #2:

The manuscript was upgraded, most of reviewer´s comments were considered in the updated version.

Research methodology was upgraded with more detailed description of activities in the specific phases. There is a good example of an armrest - a comparison between the previous and new compact armrest.

However, it would be helpful to see the whole data chain with all implementation details at least for a selected example (data examples, data quantity, data format, etc.). The manuscript reader has a good overview of the final results and all applied tools. But a research paper shall present some hidden details in background on how the case study was conducted.

Thanks for your comments, data cannot be directly reported due to NDA with the company and privacy issues with users', but we obtained the permission to publish the overview on the final results, as you mentioned. We think that this can be enough to make the reader understand the usefulness of the proposed methodology and validate it on real cases.

Additional comment:

“Five users were monitored during tests on the as-is truck model using the proposed setup, to define the typical users' actions”

How was this 5 users selected? Are they professional drivers? Are they familiar with such or similar operating environment? The reviewer assumes that driver´s previous experiences have a dominant impact on how do they conduct the test? Especially if the environment is more complex? It might be an advantage to have two groups: new users and experienced one?

The typology of users has been better described in the text, in Section 4.1 and 4,2 respectively for UC1 and UC2.

About UC1, we synthetically reported that we involved 5 target users. We explained in the test that these users are well-experienced, professional and get use to drive such tractors in similar operating environments. In this specific case, the attention was focused on expert drivers, and did not make sense to have a comparison with novice users.

About UC2, we explained in the text that users were expert in driving tractors, but with a different level of familiarity with VR technologies in order to monitor the eventual impact of the technology on the achieved performances. As in UC1, the attention was focused on expert drivers, and did not make sense to have a comparison with users with no experience in tractor driving.

“... the proposed method is faster and more efficient thanks to virtual simulation ...” The updated version present advantages of the presented approach in the discussion section. Is it possible to specify with quantitative data what effort (researcher days) is needed to conduct such analyses and design improvement - for better practical orientation?

In section 4.3 a more detailed description of the main differences between the traditional approach and the virtual approach is provided. A quantification of the effort is hard to provide because it depends on the complexity of the project. In the text, we just indicate that the different is usually from months to weeks for this study in the two modalities.