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UX Evaluation of a Tractor Cabin Digital Twin Using Mixed Reality

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Abstract. Understanding user experience (UX) is essential to design engaging and attractive products, so nowadays has emerged an increasingly interest in user-centred design approach; in this perspective, digital technologies such as Virtual Reality (VR) and Mixed Reality (MR) could help designers and engineers to create a digital prototype through which the user feedback can be considered during the product design stage. This research aims at creating an interactive Digital Twin (DT) using MR to enable a tractor driving simulation and involve real users to carry out an early UX evaluation, with the scope to validate the design of the control dashboard through a transdisciplinary approach. MR combines virtual simulation with real physical hardware devices which the user can interact with and have control through both visual and tactile feedback. The result is a MR simulator that combines virtual contents and physical controls, capable of reproducing a plowing activity close to reality. The principles of UX design was applied to this research for a continuous and dynamic UX evaluation during the project development.

Keywords. Human-centered Design; Digital Twin; Digital Engineering; Mixed Reality; User experience design.

Introduction

The ability to meet the user's needs and expectations are the core of the success of a designed product; for that purpose, the designers of the last decade are growing their interest in a human-centred design approach and User eXperience (UX). In this context, user feedback is crucial especially in the early stages of development when everything is still changing and can be adapted; in this perspective, implementing a virtual prototype is a good opportunity to obtain preliminary user feedback. This approach allows companies to test and optimize the characteristics of a product in the virtual world before the physical changeover, thereby driving down machine setup times and increasing quality [1]. The evaluation of a product in VR should be based on a multisensory simulation to offer an experience as realistic as possible that can record reliable results [2]. Moreover, the creation of multisensory environments requires a certain effort in the initial stage of the process but these simulations could be useful to collect users feedback through rapid prototyping based on VR tools. This research was aimed at creating an

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interactive Digital Twin (DT) within a Mixed Reality (MR) context for a tractor driving simulation by applying the human-centered design (HCD) principles. The model validation and verification of the control dashboard was carried out by a transdisciplinary approach, involving people from both science and practice [1]. In this work, interactive simulation for engineering purposes combines a virtual scenario controlled by physical hardware devices (joystick, steering wheel and leap motion) that allow users having visual and tactile feedback. In particular, the simulator reproduces a lifelike plowing activity, with its details and peculiarity, of a specific tractor, the New Holland model T7, produced by CNH Industrial, in which the user can test the design of the control dashboard of the tractor cabin; taking into account the final scope of the project that is helping developers to produce more usable products. [3] As a result, the outcome of this transdisciplinary process is an improved decision-making capacity of the design team [4], based on the user experience assessment. Following the principles of UX design, the evaluation phase was not only the last of the cycle but went hand in hand with the development of the project. An expert user of the agricultural sector, with long lasting experience of field test activities with tractors and the plowing process, had continuously evaluated the progress of the project to make effective changes taking advantage of multidisciplinary design optimization.

1. Research background

1.1 Principles of UX

In 1987 Whiteside and Wixon, two computer engineers, were the first to use the term user experience in the usability engineering magazine Human-Computer Interaction-Interact '87: “[U]sability exists in the experience of the person. If the person experiences a system as usable, it is. A commitment to designing for people means that, at base, we must accept their judgment as the final criterion for usability… The starting point for usability engineering must be the uncovering of user experience.” [5]. For the first time in the history of design, attention was placed on the user and his demands and not only on the product features, so the design must be aimed at creating a usable product that satisfies the user's needs. Therefore, the term UX means what users feel before, during and after the interaction with a product or service, or rather, the experience that the product or service arouses in the user in terms of usability, ease of use and satisfaction of their needs. A winning product is one that positively excites the user. Since 1999, the ISO 13407 standard "Human-centered design processes for interactive systems' ' establishes a general approach, in order to apply the concepts of HCD through a circular iterative process that apply methods and practical tools, consisting of well-established activities that contain approaches of good design. The ISO standard theorizes a practical design method called UX design cycle, that consists of four fundamental phases to be followed for a design aimed at improving the UX.

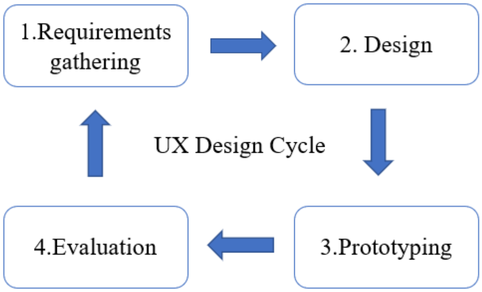

Figure 1. UX Design Cycle.

1.2 Digital Twin using Mixed Reality

There is no unique definition of Digital Twin (DT), but it highly depends on the application field in which it is used and assumes different meanings. For example, NASA sees this concept as a virtual mirror of the physical counterpart that uses both dynamic sensor data and historical product lifecycle data [6]. On contrary, the DT concept applied to the manufacturing area can be seen as a digital representation of real-world components that mirrors the real component's status, functionality, and interaction [7], that allows collaboration between the various company sections, to obtain control of the entire production process [8][9][10]. In other words, the term digital twin can be described as "a digital copy of a real factory, machine, worker, etc., that is created and can be independently expanded, automatically updated as well as being globally available in real-time." is the definition of DT in an industrial context presented by Brenner [11]. In this perspective, the DT can be utilized during the different design stages to evaluate a product, starting from CAD design to the creation of virtual prototypes up to simulations in a virtual environment of models to test their functioning. Unfortunately, traditional DT implementations in VR environments suffer from lack of efficient visual human machine interface while mixed reality (MR) technology provides a new possibility due to its powerful immersion and interactivity [12]. The term MR is referred at two different types of simulation:

- Takes the real environment and integrates computer-generated digital content [13];
- Takes a fully digital environment and connects it to objects of the real world [14].

In the first case, MR operates like the AR, but now the digital world is no longer passively superimposed on the real world, but can act as if it is part of it. The digital elements appear as if they existed in the physical world and the user can interact with them as if they really existed. In the second case, MR operates like VR: the user only sees the digital world, but it is connected with the real one, the real office walls appear digitally like industrial ones.

Our research refers to the second definition of MR, meaning the use of both virtual and physical items for the creation of a driving simulator based on a tractor DT as a design support tool, in order to simulate and optimize the dashboard of the tractor cab from an HCD perspective. Regarding DT in the agriculture sector, a tractor driving simulator was developed and constructed by Gonzalez et al. [15]. to evaluate the use of driving simulators for training programs to minimize occupational risk involving a sample of people to test it. With a similar approach, Goedicke et al. [16] evaluated operators' performance in the quality of interaction in the use of driving interfaces.

2 UX-based Digital Twin development

2.1 Methodology for the creation of the UX-based Digital Twin

The proposed methodology is developed to create a vehicle DT and is based on UX design principles, as presented in the previous paragraph, considering the four phases of the UX design cycle: requirement gathering, alternatives design, prototyping, and evaluation. In this research, a transdisciplinary approach is used, merging different fields of knowledge: the UX design cycle provides the theoretical background on which the DTs are designed and accordingly developed by the use of virtual and mixed reality tools, so this method merges the UX designer world to the VR developer's one. People experienced in the automotive field are involved in the first and the last phase of the UX design cycle, ensuring a connection between the research work and its practical application. More in detail, the creation of DT is composed of several phases; the first concerns the user research phase, in order to define a list of requirements to be implemented in the DT, extracted from on-field observation and interviews with real users. Moreover, the task analysis technique allows the definition of the main tasks carried out by the user in the real context of work. The second phase deals with the design process, in which a series of design alternatives are proposed in order to meet the requirements listed in the previous phase. Successively, in the third phase are virtually prototyped the design alternatives, through the use of VR tools and features in a MR environment. The last phase is dedicated to the UX assessment of the developed prototypes carried out with pre and post questionnaires. The pre-questionnaires investigates the users' familiarity with VR tools, gaming consoles, and driving simulators, and the previous user knowledge about the specific simulated activity. The post-questionnaire uses a 5-point Likert scale (level 1 = bad evaluation, level 5) to understand the level of immersion, easiness of executions of the various tasks and interaction with the DT. The post-questionnaire collected subjective users' judgments to verify that the virtual prototypes effectively satisfy the users' expectations.

2.2 The case study: the plowing digital twin

The case study considered the plowing activity performed by a specific tractor, the New Holland T5, representing one of the best-selling tractors from CNH Industrial performing one of the most common activities in the agriculture sector. According to the proposed methodology, real users on the field were observed and interviewed. The list of tasks was formalized by task analysis to understand which are the most crucial and frequent tasks carried out by the tractor operator during plowing, focusing on the interaction with the cabin commands. As a result of the task analysis, the list of activities performed by the operators during the plowing, is: the driving of the vehicle (from the farm garage to the field), the coupling, the unhooking, the lifting and the rotation of the plow and the plowing activity on-field.

To accomplish these tasks, operators have to use a series of commands and relative functions in the real context of use:

- Steering wheel;
- Multi Functional Handle (MFH) lever to change the direction of travel, to accelerate/decelerate and to move the posterior hooks;
- Electro-Hydraulic Draft Control (EDC) control to move posterior hooks in a more precise way and to adjust the draft during the plowing task;
- Remotes valves to couple the plow, rotate it and adjust the opening angle;
- the Main Control Panel to activate driving functions (4WD and Differential lock);
- Pedals to accelerate/decelerate the tractor;
- shortcut buttons that open screens on the main display to set the working parameters.

During task execution, the tractor operator needs to visualize working and machine settings that are currently available from different screens located in the cabin.

3 Application to the use case

3.1 Requirement gathering and task analysis

According to the UX design cycle, the project started with the collection of users data relating to the plowing on field, through user observations and interviews. From these techniques it was possible to extract the task list of the operations for a standard plowing activity and the related commands on the tractor cabin. In particular, the result of the task analysis is shown in Table 1.

Table 1. Task analysis.

Tasks	**Commands**
Lower the posterior hooks	MFH, EDC
Hook the plow	MFH, EDC
Lift the posterior hooks	MFH, EDC
Driving to reach the field	steering wheel, pedals, MFH
Lower the plow	MFH, EDC
Insert 4WD and Diff Lock	4WD and Diff Lock buttons
Plowing	steering wheel, pedals, MFH

Finally, the last step consists of the definition of the requirements list, expressing demands and wishes to drive the design of the DT and the arrangement of a realistic simulation.

3.2 Design alternatives

Once the requirements list is completed, the following step is the creation of two design alternatives of DT, specially in terms of user interaction experience, to improve the overall UX. Therefore, this phase aimed to design the features of the DT, such as the virtual controllers to replicate the user interaction with the dashboard and the commands in a virtual scenario, simulating a life-like plowing activity according to the selected case study. For example, interaction with the tractor could be controlled by a joystick, replicating the multi-functional handle of tractors, or by a set of push-buttons. Two alternative designs of the DT were conceived, implying the use of different types of controllers. The first design (DT1) uses a full kit driving controller, composed of steering wheel, pedals and push-buttons, commonly used for gaming experience. The second design (DT2) uses a different controller set-up that mixes together the steering wheel, a cloche joystick and a hand-tracking device. Table 2 sums up the different controllers' configurations for the two alternative designs, with respect to the functions to be replicated in the system. Such alternatives were prototyped and assessed as described in the following paragraphs.

Table 2. Controllers and their functions in the two design alternatives.

Functions	**DT1**	**DT2**
Steering function	Steering wheel	Steering wheel
Acceleration/Deceleration	Pedals	Joystick
Plow rotation	Push-buttons	Hand-tracking device
Plow lifting	Push-buttons	Joystick button
Differential Lock and 4WD	Push-buttons	Hand-tracking device

3.3 Prototyping using immersive MR simulation

Two different prototypes were developed to differently simulate a tractor cabin in the MR environment replicating the main tasks of the plowing. The prototypes involved the use of the following tools:

- Unity3D: platform for the creation of interactive 3D contents and the design of the virtual scenes;
- Leap Motion: hand-tracking and gesture recognition system for the human interaction with virtual items, based on the use of infrared cameras;
- HTC Vive Pro Eye: head-mounted display (HMD) used for the true-to-life and high-resolution visualization of the virtual contents;
- Steam VR: platform to manage the VR devices;
- Logitech Extreme 3D Pro: cloche for flying simulation and gaming purposes, adopted to replicate the tractor multi-functional handle;
- Kit Logitech G Saitek Farm Sim controller: full kit with steering wheel, pedals and push-buttons user for farming simulator gaming.

In order to develop the prototypes, a virtual scenario was created related to the peculiar use case, using Unity 3D platform. Then, 3D models of the specific tractor were imported into the scene, in .fbx format. At this point, the behaviors of the virtual objects in the scene were set, according to functions listed before and the features of the real tractor. Virtual objects could be simply visualized by users or could offer an interactive behavior. Interactive objects require a specific setting in order to define their movements, behaviors and constraints in the scene. For example, the MFH could be only moved by pushing or pulling. These behaviors could be set in Unity3D by combining default features and ad-hoc scripts in C# language customized for the specific application. Finally, an advanced graphical rendering of the simulation scene was developed in order to obtain an impressive virtual cabin, very close to reality. Moreover, the area to be plowed was reproduced with a terrain able to simulate the real effect, such as change of color, creation of the groove and the dust effect. Figure 2 shows the set-ups for the two different prototypes. Conversely, Figure 3 and Figure 4 shows the plowing activity from the rear and cabin view.

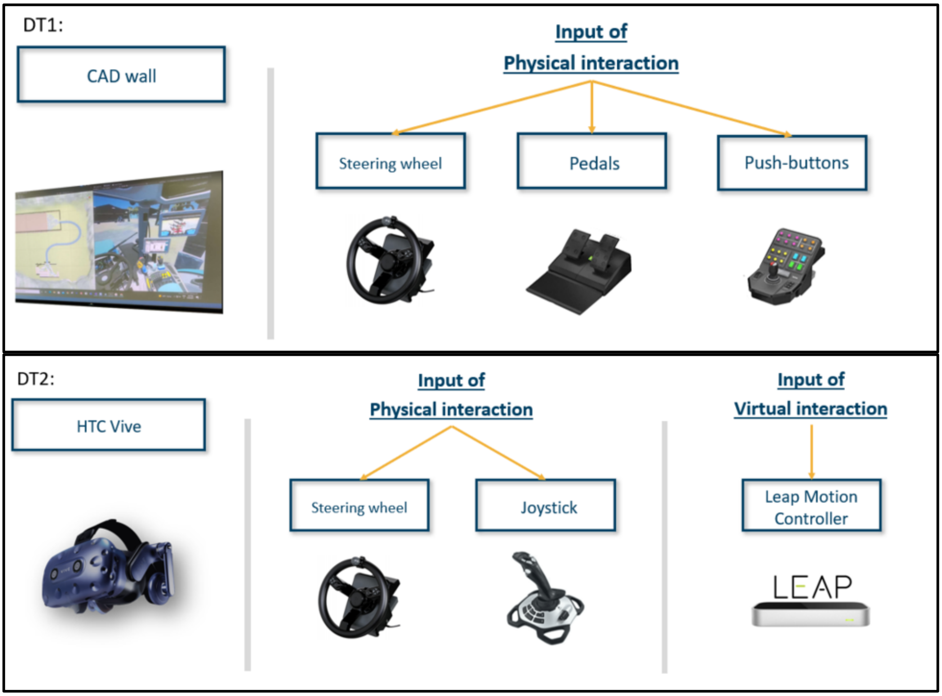

Figure 2. Technological set-ups for the two prototypes.

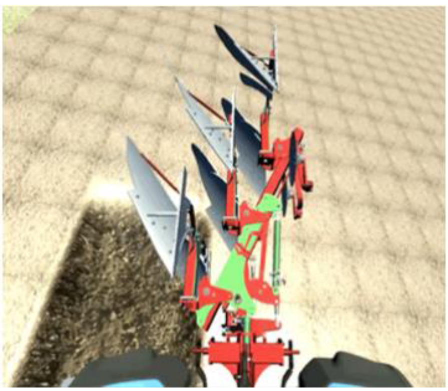

Figure 3. Plowing activity (rear view).

Figure 4. Plowing activity (cabin view inside the tractor).

3.4 UX evaluation and results

The UX evaluation phase took place in the Virtual Room of the Xilab laboratory, of the University of Modena and Reggio Emilia. A sample of ten users was involved: from 25 to 35 years old (9 men, 1 woman), with previous experience in the agricultural sector and medium familiarity with VR devices, so that users tried some VR systems at least once. Users tested the two different DT prototypes developed in the study. The main objective of the tests is the UX evaluation through questionnaires that investigates three main indicators: immersion, easiness of use and interaction with controllers of the tractor DT and MR simulations, to support dashboard design in the future. A set of questions for each indicator were reported in Table 3.

Before the test, the user was informed about the task sequence to understand what is the correct procedure to accomplish the test. An informed consent document was used to provide subjects with the information they need to make a decision to volunteer for the research study.

Figure 5. Example of user testing on the two prototypes (DT1 on the left and DT2 on the right).

In Table 3 are presented the results emerged during the testing phase; in detail, the average values of the ten users for each question are reported.

Table 3. UX evaluation of the two DT prototypes.

Categories	Questionnaire statements	DT1	DT2
Immersion	I felt immersed in the scene	2.4	4.7
	I think the scene is very realistic	4.1	4.2
	I felt involved in the scene	3.7	4.8
	I didn't feel like I was in a video game	3.6	1.9
	I didn't feel sickness	5.0	4.7
Easiness of use	I felt very confident using the system	4.3	4.6
	I can use it without written instructions	2.9	3.4
	I learned how to use it quickly	3.4	4.4
	I thought the system was easy to use	3.9	4.0
	I easily remember how to use it	3.2	4.6

Categories	Questionnaire statements	DT1	DT2
Interaction with controller	I think that controllers were well integrated in the system	3.9	4.7
	I think that the command assignment to push-buttons and joystick is suitable	4.1	4.5
	I felt comfortable during the driving	4.6	4.6
	I had the complete control of the scene	4.5	4.3
UX score (mean value)		**3.8 (s.d. 0.7)**	**4.2 (s.d. 0.8)**

As highlighted in Table 3, the general UX score of the two DTs proposals (mean value of the average scores for each question about different DTs) is higher in the second version proposed, mainly due to the more immersive experience. On the contrary, DT1 is preferable for users more sensitive to VR sickness.

4 Conclusions

The paper proposed a transdisciplinary methodology to create a UX-based, MR interactive DT for a tractor driving simulation. The application of UX design techniques helped the definition of a robust methodology to design the DT according to a user-centric perspective. MR was useful to rapidly prototype the cabin dashboard and carry out an early design evaluation and model validation by user testing. Two different DT prototypes were developed and compared, in terms of immersion, easiness of use, and interaction with controllers. The main contributions of the paper are as follows: from a methodological point of view, the research adopt a transdisciplinary approach based on the involvement of UX design principles to develop a DT in MR for agricultural sector; from a technical point of view, the research merges different fields of knowledge in order to give the user true-to-life simulations, synchronizing VR tools and physical controllers in a MR environment. From the analysis of the results, the second version of the MR prototype (DT2), realized by steering wheel, joystick and leap motion, was more usable and intuitive for users. The main limitations of this study are the limited number of user testing due to the Covid pandemic situation and the lack of an objective UX evaluation. Moreover, as a future development, the comparison between the real tractor and the virtual one could be investigated involving a sample of real tractor drivers from the company's field test team. In conclusion, the study demonstrated how to create a DT developed in MR by synchronizing VR tools with the physical devices, and how to use it to early assess the UX to test products in advance and collect the users' impressions and feedback.

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