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Abstract: Virtual reality (VR) training allows companies to train their workforce thanks to virtually simulated environments, leveraging the skills of people before the system production, with the final aim to reduce the downtime of productive equipment and improve the global factory efficiency. However, the use of VR immersive training is still limited in industry due to the lack of structured methodologies to effectively implement these simulations. This paper deals with the application of VR technologies to create virtual training simulations addressing assembly or maintenance tasks. It suggests a methodology to create an interactive virtual space in which operators can perform predefined tasks in a realistic way, having dedicated instructions to support the learn-by-doing, based on key training features (KTFs). This methodology was applied to an industrial case study concerning some specific tractor assembly phases. Results show that operators generally appreciate this new training process, enabling faster and more intuitive learning.

Keywords: virtual training; virtual factory; virtual reality; virtual assembly; smart factory.

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1   Introduction

Virtual and augmented reality represents one of the pillars of Industry 4.0 (I4.0) (Boston Consulting Group, 2015). More specifically, virtual reality (VR) environment includes a wide variety of computer-based simulations and highly visual immersive applications that allow the user to navigate within an apparently real or physical world (Lopreiato, 2016). These new concepts could help the integration of humans in the design and training advanced technological systems like modern factories. Indeed, human operators still play a critical role in the smart factory, but their work is rapidly evolving due to the intelligent machines and a different organisational scenario (Romero et al., 2016). This fact brings to rethinking workplaces, working tasks and the role of humans, which require further skills and abilities (Peruzzini et al., 2019). Physical tasks are gradually replaced by more cognitive-intensive activities, such as supervision and decision-making. However, manual tasks are still executed for high-precision activities and small, highly customised productions. For these reasons, it is necessary to also rethink the workers' training methods to properly support this evolution. Nowadays, training is usually carried out by reading manuals and supported by more skilled operators, who train the less experienced ones; this procedure is time consuming and generally carried out at the real shop floor.

In the context of I4.0 development and the simultaneously widespread diffusion of digital technologies, the industrial world is opening up to new possibilities and ways of educating operators in the field of maintenance (Eschen et al., 2018) or assembly (Peruzzini et al., 2020). The technological progress and the consequent cost reduction of VR technologies like head-mounted displays (HMDs) and hand gesture recognition,

historically developed for gaming, have started to spread in different fields, from marketing, to medicine and industry. Consequently, researchers have recently developed various applications for virtual training for different purposes, without defining formalised procedures for industrial contexts (Wong et al., 2010).

This research aims to improve the training of industrial operators by a learn-by-doing methodology based on virtual practices using low-cost and minimal setup: a VR graphics engine to develop the virtual world, a VR HMD to immerse the user in the virtual world, and a gesture recognition device for bare hand tracking. The study takes into account the assembly of an after-treatment system for tractors: the procedure was firstly analysed on the field, observing real users trained with traditional methods (i.e., paper-based manuals), and then implemented into a new virtual training scenario reproducing the real plant enhanced with specific features, called key training features (KTFs). The research also compared the traditional and virtual training modalities and investigated the possible advantages for the company by virtual training applications.

The research provides two main scientific contributions:

- We defined a structured methodology for the practical adoption of virtual training procedures in industry for assembly purposes, based on the adoption of KTFs.

- We assessed the KTFs-based training according to the usefulness perceived by users in order to understand and classify these training features.

The paper is organised as follows: Section 2 describes the related literature, Section 3 presents the proposed methodology, Section 4 deals with the validation on industrial cases, Section 5 discusses the obtained results, Section 6 is about the conclusions.

2 Related works

In recent years, the technological shift has led to lower demand for labour in jobs in which routine tasks predominate. This has especially increased the demand for highly multi-skilled workers (European Commission, 2018). Indeed, I4.0 radically changed the role of frontline operators: they not only perform physical jobs, but also more demanding cognitive tasks, such as process supervision, machine programming or decision-making in exceptional conditions (Madonna et al., 2019). Moreover, an experienced and multi-skilled training should help boost the manufacturer's productivity, decrease employee turnover, and solve the talent gap as well as level the workforce preparation, reaching better product quality at lower costs (Małachowski and Korytkowski, 2016). In this context, it's crucial to provide proper training to the workers from the early stages of production, to reduce the lead time (Boothroyd, 1996). However, manufacturing industry training can be expensive and time-consuming, as it requires the extensive involvement of trainers and supervisors to teach employees the necessary skills and processes. One possible solution to this problem could be the adoption of e-learning courses: these not only provide a more cost-effective alternative to classroom or on-field training, but it is also much more flexible, enabling study out of working hours (Hartmann et al., 2019). However, most computer-based training systems are not lifelike enough to completely substitute conventional face-to-face training in complex manufacturing. This is partially due to the fact that in real life workers have access to physical equipment and tools which they manipulate (Gonzalez-Franco et al., 2017). Training effectiveness can be enhanced

by providing operators with a sense of realism. Moreover, traditional training methodologies can be inadequate to instruct the operators for seldom-occurring risky operations, that cannot be easily replicated in a real context (e.g., safety-critical contexts, chemical industry, continuous flow systems, nuclear power plants) (Patle et al., 2014). Furthermore, also when conventional training is generally effective, it usually lacks to give operators the actual awareness of the global ongoing process.

In this direction, VR offers a safe digital environment in which a user can interact intuitively with the digital parts, learning-by-doing instead of learning processes by seeing, listening, or observing (Abidi et al., 2019). Indeed, VR provides users the opportunity to freely explore virtual objects, using enhanced simulations to achieve the proper level of detail as required by the work activity (Boud et al., 1999). VR simulation can also replicate emergency conditions, accidents, and investigate safety protocols (Patle et al., 2019) proving an immersive experience without risks (Pérez et al., 2019), to easily replicate safety-critical operating scenarios in order to train users in highly stressed conditions (Pedram et al., 2020). In addition, VR seems to be an effective tool for applying sustainability; in the latest I4.0 paradigm, virtual technologies have been emphasised to sustainably train and educate young students (Salah et al., 2019). These principles could be applied in the assembly context, in which assembly operations account for a significant amount of time and cost in the product development cycle (Fatima et al., 2018).

The application of VR for assembly purposes has been defined as virtual assembly (VA). VA consists of interactively analysing and simulating the assembly operation process together with the product assemblability, as also stated by Xia et al. (2013). VA could be also considered as an emerging training mode with respect to the traditional methodology, based on an experienced trainer responsible for transmitting the knowledge and skills to the trainee, using real machines, line or components (Peniche et al., 2012). In the same way, usual working instructions are provided in complex standard operating procedures (SOPs) guide, based on a few pictures and text where the expected manual gestures may be hardly understood. In this context, VR approaches allow realising an effective training of particular manipulation gestures that are vital for specific assembly and maintenance procedures (Numfu et al., 2019). In a virtual environment, the assembly target could be displayed in a clear mode, rendered in real-time from the user viewpoint, in an adaptive way, allowing a strong immersion and improving the smoothness of the assembly operation. In the same way, modern VR technologies can support multi-user co-located collaborative operation, which is more in line with the real assembly environment (Zhao et al., 2019). For instance, Zou et al. (2019) used a VR system based on the Unity 3D platform to train operators in assembly and disassembly of a Boeing landing gear, comparing the virtual procedure with the traditional training methods and demonstrating how virtual mode can significantly improve the ability of maintenance workers, reducing the overall cost and improving the training efficiency. Moreover, Etemadpour et al. (2019) investigated the role of different visual cues (i.e., image and text) on user performance while performing manual assembly in an immersive virtual setting and a non-immersive, desktop-based environment; results showed that, for certain tasks, immersive virtual training can be faster and more accurate than desktop-based training.

The state of the art highlighted the great potentiality of VR for industrial training, but also the lack of structured approaches to develop efficient training procedures to fully exploit the learn-by-doing approach in industry.

3   Methodology

The aim of the paper is defining a methodology to create virtual immersive training sessions. The final scope is to drive companies, interested in virtual training, to understand how to effectively implement virtual practices according to their specific process needs, and to measure the potential benefits. The method has been proposed and tested for VA application; however, it could be easily adapted also to virtual maintenance or other virtual training scopes. The methodology is outspread in the following subsections, detailing the approach and the adopted technological setup.

3.1   The virtual training approach

The proposed approach is based on the insertion of specific features, called KTFs, to support the virtual training procedure. The KTFs are conceived by observing workers during assembly training sessions in real context, in different industrial contexts, from automotive to commercial vehicles, agricultural machines, and automatic machinery. From the analysis, several difficulties about detecting the right assembly parts or positioning them in the correct position emerged. Moreover, operators usually waste a lot of time in consulting paper-based manuals, interrupting their manual work and reducing their mental concentration. As a consequence, a set of KTFs were defined to help workers to remind the correct assembly sequence and reduce their mental workload. These KTFs act as training guidelines to assist the workers step by step, appearing in the virtual scene contextually and adaptively to the user's needs. These features can be easily implemented in any VR development platform (Unity 3D or others). The definition of KTFs helps the virtual training implementation and provides a structured training procedure as highlighted in literature.

According to the proposed approach, a set of KTFs has been conceived for the specific VA application, to guide the worker throughout the VA journey promoting learning-by-doing. The defined KTFs are listed and described as follows:

- *SOP instruction image:* It is a visual representation, consisting of one or more bidimensional images, driving the user in executing a task. It can be taken from the training manual or specifically realised for the virtual procedure, but in both cases, it automatically appears only when necessary, thanks to specific simulation triggers (e.g., when the user stands in a certain area, when the user grips a specific object, when the user executes a predefined action). It is usually located into a dedicated instruction panel, frequently positioned in front of the assembly area, or anyway in a highly visible position.

- *SOP instruction text:* It is a concise textual label generated during the process, containing very important information (e.g., tightening torque). Also in this case, it can be taken from the training manual or specifically realised for the virtual procedure, but in both cases it automatically appears only when necessary, thanks to specific simulation triggers. It is usually located into a dedicated instruction panel, frequently positioned in front of the assembly area, or anyway in a highly visible position.

- *Arrow guideline:* It is an arrow, rendered with an evident colour (e.g., red), highlighting the correct part to choose and grasp during the assembly procedure. It automatically appears when necessary, for instance when the previous part has been positioned in the right location.

- *Ghost guideline:* It is the ghost of the original part, associated with a transparent material and located in the correct mounting position, to drive the user's understanding about the assembly sequence to realise. It automatically appears when the part has been grasped by the user, to indicate how to properly assemble the part.

- *Part number:* It is an alphanumeric label attached to specific items to recognise them properly by their number. It is usually highlighted with an evident colour (e.g., red) and positioned above the referenced item. It permits the unambiguous identification of standard parts (e.g., screws and washers).

- *Warning:* It is a highlighted textual information that alerts the user when the procedure is hardly to accomplish or is particularly critical for some specific reasons. It is usually located into the dedicated instruction panel together with the SOP instructions.

Figure 1 Examples of KTFs, (a) arrow guideline and part number (b) SOP instruction and ghost guideline (see online version for colours)

(a)   (b)

According to the proposed approach, the creation of the VA training procedure starts with the generation of the virtual environment as a copy of the factory physical layout, for a realistic impression. Subsequently, it implements the specific assembly procedure and the definition of the most proper KTFs to support the training process. Features are classified also according to the type of application, general or specific. General KTFs are applied during the entire training sequence, while specific KTFs are used when the task is particularly critical to highlight specific critical reasons.

The process to create the virtual training simulation requires seven steps as listed below.

- Phase 1: Creation of the virtual scene using a VR platform (e.g., Unity3D), importing and rendering 3D models to recreate the workstation layout or importing captured 3D data from real environment scanning.

- Phase 2: Identification of the assembly tasks and definition of 'movable' objects and basic interactions of workers, on the basis of process task analysis.

- Phase 3: Setup of the HMD for user tracking and user point of view (e.g., SteamVR in Unity 3D).

- Phase 4: Setup of the hand gesture recognition controller (e.g., Leap Motion) and integration with the VR platform, to make the user interact with virtual objects using bare hands.

- Phase 5: Implementation of the assembly procedure by identifying the sequence and the interactable parts.

- Phase 6: Definition of general KTFs (related to the overall assembly sequence) and specific KTFs (related to critical tasks).

- Phase 7: Creation of general and specific KTFs and application to the VA training application.

Figure 2 Step-by-step methodology to create the virtual training simulation (see online version for colours)
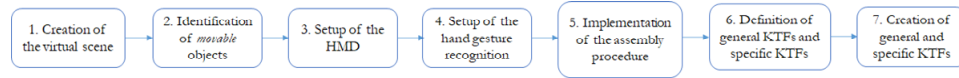
For the specific study, all KTFs (as depicted in Figure 3) have been created using Unity 3D. Table 1 sums up the KTF classes and describes how each typology has been realised using the specific Unity 3D components (technical items are below in italics).

Figure 3 Examples of KTFs during virtual training (see online version for colours)

After the VA training creation, users can wear the HMD and perform the task assembly sequence immersed in the virtual scene, with their bare hands. The use of bare hands, guaranteed by the hand gesture recognition controller, is particularly important to assure a realistic and reliable simulation, very close to reality. During the simulation, users follow the proposed training procedure without using any manual or interacting with the trainer. Users were free to navigate and work in the virtual scene: experts can observe

them during task simulation to collect the execution time or time data can be automatically collected by the video streaming of the session.

Table 1   KTFs description and implementation in unity 3D

Key training features	Type of application	Graphical information	Involved Unity 3D components
SOP instruction	General	Panel with images	*Sprite 2D*
		Panel with texts	*Text mesh*
Ghost guideline	General	Twin object in transparent material	*Gameobject with anchor script*
Arrow guideline	General	Arrow CAD in red material	*Gameobject*
Part number	Specific	Identifying code	*Text mesh*
Warning	Specific	Advertising test	*Canvas*

After the virtual training session, users are asked to fill in a post-test questionnaire in order to validate the proposed method and assess the usefulness of the KTFs. The questionnaire considers the classes of KTFs shown during the simulation: for every class, users have to express their judgement using a five-point Likert scale (0 means that the KTF is not useful, five means that the KTF is extremely useful).

3.2   Experimental setup

For this study, the implemented technological setup included a commercial HMD (HTC Vive), equipped with a hand gesture controller and four infrared base stations that extend the user tracking in a 4 × 4 metres physical space, transformed into a virtual one. HTC Vive was chosen since it uses a robust room scale tracking technology to virtualise a physical space, in which the user can move itself freely, in order to guarantee a 360-degree tracking of the user. For hand gesture recognition, a Leap Motion controller was used to make users grasp virtual objects in the virtual environment in an intuitive manner with bare hands. The Leap Motion controller sensor was placed on the centre of HTC Vive with a specific support. Finally, as a VR build platform Unity 3D was used to allow the flexibility of development and the possibility to implement different training features. In particular, every system is described below:

- Unity3D: It is a game development platform for the realisation of interactive 3D virtual content; it provides all necessary for designing virtual scenes and implement lifelike features such as physics. Moreover, it allows graphics rendering of every single parts and environment of virtual scenario.

- HTC Vive: It is a wearable HMD equipped with two Fresnel's lenses to adjust the interpupillary distance (IPD). It consists of 32 infrared sensors to permit the 360-degree tracking; furthermore, the gyroscope, the accelerometer, and the laser position sensor of which is made up create a tracker with six DOF. The HTC Vive requires SteamVR software to be controlled into a Unity scene. Both HTC Vive and HTC Vive Pro Eye are suitable for the study purposes.

- Leap Motion controller: It is an optical hand tracking system that allows gesture recognition. Each finger position is captured by two monochromatic IR cameras and three infrared LEDs and virtualises the user's hands through mathematical algorithms.

The proposed approach can also be implemented using any other commercial HMD (e.g., Oculus Rift and Samsung Gear).

The immersive virtual training setup was realised by the following software architecture: Unity 3D, Leap Motion control panel, and SteamVR are installed on the same workstation. During the simulation, the user was wearing the HMD while the SteamVR allowed the user head tracking in the virtual scenario. Simultaneously, the Leap Motion control panel allowed the user hand tracking in the virtual scene.

4 Validation on industrial use cases

4.1 Industrial use case description

The use cases were defined and developed in collaboration with CNH Industrial, a global leader in design and manufacturing of agricultural machines, buses, and trucks. In particular, the on-field analysis has been carried out in two different company production sites: San Matteo plant (Modena, Italy) and Noida plant (India). The proposed virtual training methodology was validated on industrial cases, as different phases during the assembly of the selective catalytic reduction (SCR) on medium-sized tractors. In particular, the research focuses on three assembly sub-sequences, identified as the most critical ones in the entire process, according to the company workers' opinions collected by interviews. Main issues were related to a low understanding of the correct assembly procedure, which generates delays in production, as reported by the interviewed workers.

Only the three critical sub-sequences selected have been virtualised and tested in the research. They are described as follows:

- Use case no. 1 (UC1): Fixing the SCR to the main support. The operator has to position the SCR muffler on the main SCR support and fix it with three bushing washers and bolts.

- Use case no. 2 (UC2): SCR heat shield mounting. Firstly, the worker has to mount a safety bracket with different washers and bolts on the SCR muffler and later has to assemble the heat shield.

- Use case no. 3 (UC3): Temperature, NOX and NH3 sensors subassembly. The operator has to screw the sensors inside the specific housings on the SCR.

In UC1 operators usually have some difficulties to reach the bush housing, forcing them to assume incorrect postures that could lead to musculoskeletal disorders. Instead, in UC2 workers could confuse the two different washers needed for the fixing of the safety bracket. Finally, in UC3 the main problem is related to the correct orientation of the sensors' cables and frequent human errors due to confusion between different sensors.

The standard procedure to train operators in the selected assembly sequence is supported by paper-based instruction, as represented in Figure 4. Workers generally have

a printed copy of the SOP at the assembly line and are trained using images and textual descriptions.

Figure 4   Example of traditional SOP instructions (see online version for colours)
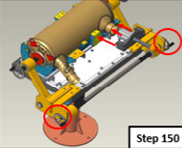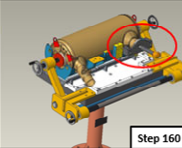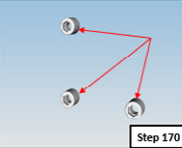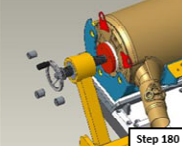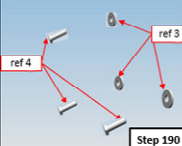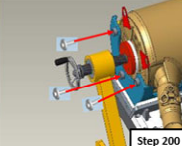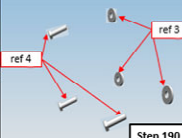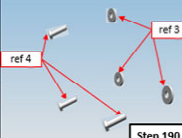

Table 2   Virtual training session tasks for UC1 'fixing the SCR to the main support'

Task's description	Tools used	SOP instruction	Ghost guideline	Arrow guideline	Part number	Warning
1 Insert the SCR gauge pin in the main support bracket	-	●	●	●	-	-
2 Adjusting the SCR muffler rotating the fixture wheel	-	●	●	●	-	-
3 Insert and tight three bushing in the holes of main support bracket	Allen key	●	●(*)	●	●(*)	-
4 Torquing the bushing 0.5 kg-m	Torque wrench	●	-	-	-	-
5 Insert three bolts and washers in the three SCR bushing	-	●	●	●	●	●(*)
6 Tight bolts with washers	Socket or pneumatic gun	●	-	-	-	-

Note: *these KTFs are reported also in Figure 5.

The new virtual training procedure started from the analysis of the SOP instructions, providing the tasks description and sequence. Workers were also observed at the real shop floor to better understand their tasks. The combined analysis of instruction and observations supported the identification of the task sequence to virtualise for each use case. Moreover, for each case the most proper KTFs were defined and extracted from the SOP if needed. Subsequently, the virtual training scenario was developed. In order to apply the learning-by-doing approach, the above-mentioned KTFs were implemented in the simulation, with the aim of helping workers overcoming the most critical phases as reported by interviews.

Figure 5 Examples of KTFs implementation for UC1 (see online version for colours)
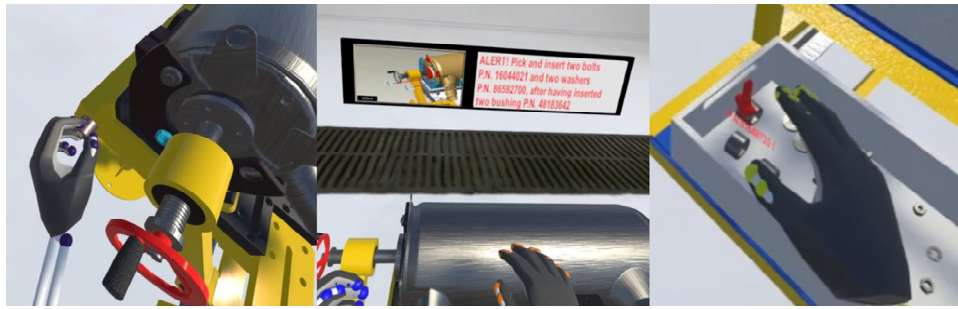
Tables 2, 3 and 4 describe the main tasks implemented in the virtual training scenario and the related KTFs, for each use case.

Table 3 Virtual training session tasks for UC2 'SCR heat shield mounting'

	Task's description	Tools used	SOP instruction	Ghost guideline	Arrow guideline	Part number	Warning
1	Pick the heat shield	-	●(*)	●(*)	●	-	-
2	Pick the three bolts	-	●	●	●	-	-
3	Pick two helical lock washers 0.8 and two washers 0.8 × 17 (×3)	-	●	●	●(*)	●(*)	-
4	Assemble the heat shield SCR with the main support bracket	-	●	●	-	-	●(*)
5	Tight bolts with washers	Socket or pneumatic tool	●	-	-	-	-

Note: *these KTFs are reported also in Figure 6.

In UC1, as shown in Figure 5, a ghost guideline was implemented as KTF in order to better show the positioning of the bushing houses. In addition, an instruction panel located in front of the workbench allowed visualising two types of information: on the left side the image depicting the right task (directly taken from the SOP) and on the right

side any possible warnings. Such instructions are dynamic and updated at every single task to support the operator through the training session. For small parts like bushing, bolts and washers, arrow guidelines and part numbers KTFs were applied in order to not confuse parts.

In the UC2, as shown in Figure 6, a similar approach was used to present the SOP instructions in the virtual simulation as well as ghost guidelines were used, helping the operator to understand the correct positioning of parts in the assembly. In addition, part numbers were implemented to avoid confusion among parts, such as helical lock washers and washers with the same diameter. Finally, the arrow guideline as KTF was used to indicate the part to be handled in the correct order of assembly.

Figure 6   Examples of KTFs implementation for UC2 (see online version for colours)

The main criticality in UC3 was connected to the similarity of the three sensors, that could be confused, and the difficulty to determine their correct orientation. In order to overcome these problems, information like part numbers and arrow guidelines assumed a key role for the success of these tasks, as shown in Figure 7. Other features were implemented as in the previous use cases; among them, in UC3 warnings were fundamental to solve the orientation issue of sensors.

Figure 7   Examples of KTFs implementation for UC3 (see online version for colours)

The VA training sessions were conducted in the company lab. A sample of ten users were involved in the virtual training simulation. Five of them were assembly expert users, even if they were not familiar with the proposed use cases; five users were not-expert, being workers involved in other company areas. All of them never tried VR technologies for training purposes. The choice of the mixed sample of users (experts and novices) could lead to a holistic evaluation of the proposed training method, taking into account both the

quality and fidelity of the assembly procedure in the VR scenario and the efficacy of the hand training method.

Table 4 Virtual training session tasks for UC3 'temperature, NOX and NH3 sensors subassembly'

	Task's description	Tools used	SOP instruction	Ghost guideline	Arrow guideline	Part number	Warning
1	Pick the temperature sensor	-	●	●	●(*)	●(*)	-
2	Insert and tight manually the temperature sensor in the hole no. 1 in SCR unit muffler	-	●(*)	●(*)	-	-	●(*)
3	Pick the NH3 sensors	-	●	●	●	●	-
4	Insert and tight manually sensor NH3 in the (hole no. 2) in SCR unit muffler	-	●	●	-	-	-
5	Pick the NOX sensor	-	●(*)	●(*)	●	●	-
6	Insert the NOX sensor in the (hole no. 3) in SCR unit muffler and tight manually	-	●	●	-	-	-
7	Pick the two hex screws	-	●	●	●	●	-
8	Assemble the NOX sensor with the bracket tightening screws manually	-	●	●	-	-	-
9	Tight the hex screws	Allen socket battery gun	●	-	-	-	-
10	Torque all three sensor (specific force range)	Torque wrench	●	-	-	-	-

Note: *these KTFs are reported also in Figure 7.

Two different virtual sessions were organised per each user, one a day for two consecutive days. During the simulation, two external experts as observers monitored the execution time and the training times along the days and compared with traditional training times. After the final session, each user was asked to fill in the post-test questionnaire to understand the usefulness of the proposed KTFs and the global satisfaction, according to a five-point Likert scale.

5   Results and discussion

All virtual training sessions were completed successfully by the users involved. Table 5 sums up the KTFs adopted in the three UCs, the type of information represented and the *KTFs perceived usefulness* as the average values of ten users for the three UCs, on the basis of users' feedback expressed by questionnaires. Perceived usefulness is defined as "the degree to which a person believes that using a particular system would enhance his or her job performance" (Davis, 1989). The average perceived usefulness parameter is calculated by an arithmetic mean of the ten values expressed by each user.

Results showed that the most useful KTFs were SOP instruction images and ghost guidelines (5 out of 5). On the contrary, the less useful features were arrow guidelines in the users' opinion (2 out of 5). The success of the first two KTFs is probably connected to the intuitive visual impact that supports all users to immediately comprehend the parts to be handled and the right actions to move them. In addition, for these cases the arrow guidelines seem not necessary because users were already able to identify the proper tasks. SOP instruction texts and warnings were also evaluated positively (4 out of 5), as they gave additional detailed information to better understand the assembly sequence. Part numbers were judged averagely useful. Table 5 expresses the mean perceived usefulness of the different KTFs as average values on all users, according to the five-point Likert scale, but the research also collected sensible variations according to the users' level of expertise. Indeed, the questionnaire analysis highlighted a sensible gap between less experienced users, who see a greater support in understanding the right tasks thanks to KTFs, and expert users, who were mostly helped in identifying the correct components and respective locations. In conclusion, the users' feedback about the use of KTFs was positive.

Table 5   Mean KTFs perceived usefulness

Key training features	Type of application	Graphical information	Average* KTF perceived usefulness
SOP instruction	General	Panel with images	●●●●●
		Panel with texts	●●●○
Ghost guideline	General	Twin object in transparent material	●●●●●
Arrow guideline	General	Arrow CAD in red material	●●○○○
Part number	Specific	Identifying code	●●●○○
Warning	Specific	Advertising test	●●●●○

Note: *average on ten users on three use cases.

Finally, during the virtual sessions training times were collected, and compared with times of traditional training procedures. Also, the global training satisfaction was investigated by questionnaires. The comparison between the proposed KTFs-based virtual training and the traditional training was based on ten users on the three use cases. Results highlighted that VA training generally allowed saving time (–18% on average) and improving the global users' satisfaction (+30%). Specific interviews also found that the virtual procedure was sufficiently realistic and well perceived, layout was close to real ones and users' movements were comfortable. However, the majority of users (7 out of 10) revealed the lack of feedback regarding the physical efforts and touch sensations.

For sure, such preliminary results could be improved when the VA training procedure will be formally introduced in the company.

6 Conclusions

The state of art about virtual training in scientific research highlighted the lack of a structured methodology to effectively implement assembly instruction during virtual training sessions to introduce the VR practices within company processes. In this regard, the paper proposed a method to effectively create virtual training procedures for industrial purposes according to the learning-by-doing paradigm. It is based on KTFs introduced into the virtual scenario to guide users along the virtual training. Three use cases were developed to implement the proposed procedure and validate the proposed approach involving real users in a VR environment. The results obtained by questionnaire about the KTFs usefulness look promising. The overall score represented a positive evaluation (globally 3.8 out of 5) indicating a good user appreciation. In particular, the most useful KTFs as judged by users were respectively SOP instruction images and ghost guidelines. They were positively evaluated due to their visual impact, instead of textual KTFs that need more time and attention to be understood. The proposed methodology also proved to be flexible, allowing companies to implement the most suitable KTFs for exploiting the virtual training practice in a large field of application. The proposed approach could be also implemented using different VR setups or VR platforms.

To conclude, the implementation of the proposed KTFs within a structured methodology helps companies to effectively create virtual training procedures and to train operators with less effort, reducing time and costs. The proposed interactive training mode, much more visual and immersive with respect to traditional training, guarantees quicker and higher-quality learning. Some limitations of the proposed training consist of the simulation simplification in a few aspects, to reduce the computation effort, such as the absence of object gravity and flexibility in the object behaviour simulation. Moreover, the touch sensations are not included but only a visual feedback is provided. This fact makes specific complex operations quite challenging to reproduce in a realistic way, such as screwing operations.

Future works will focus on the addition of voice instructions as a new KTF class, that can further enrich the training sessions, and the implementation of a more realistic behaviour for flexible objects, such as cables and pipes, including also gravity simulation. Furthermore, the proposed approach could be extended to other industrial cases in various fields, such as maintenance, to compare this new training approach with the traditional one. Another follow up could be a possible cooperative assembly session carried out by more than one operator.

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