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# Using virtual reality and 3D industrial numerical models for immersive interactive checklists

P. Fillatreau<sup>a,\*</sup>, J.-Y. Fourquet<sup>a</sup>, R. Le Bolloc'h<sup>a</sup>, S. Cailhol<sup>a</sup>, A. Datas<sup>a</sup>, B. Puel<sup>b</sup>

<sup>a</sup> LGP-ENIT, INPT, Université de Toulouse, 47 Avenue d'Azereix, BP 1629, 65016 Tarbes Cedex, France

<sup>b</sup> Alstom Transport, France

## ABSTRACT

At the different stages of the PLM, companies develop numerous checklist-based procedures involving prototype inspection and testing. Besides, techniques from CAD, 3D imaging, animation and virtual reality now form a mature set of tools for industrial applications. The work presented in this article develops a unique framework for immersive checklist-based project reviews that applies to all steps of the PLM. It combines immersive navigation in the checklist, virtual experiments when needed and multimedia update of the checklist. It provides a generic tool, independent of the considered checklist, relies on the integration of various VR tools and concepts, in a modular way, and uses an original gesture recognition. Feasibility experiments are presented, validating the benefits of the approach.

### Keywords:

Virtual reality  
3D industrial inspection  
Quality and control processes  
3D visualization  
Sensorimotor interfaces

## 1. Introduction

The methods and tools for 3D imaging and interactive simulations in virtual reality (VR) have now penetrated industrial activities. They are used in particular for project (e.g. design) reviews, or for the implementation of Computer Aided Design (CAD) models in manufacturing industries [34,16,19]. This is particularly the case in the activities connected to the aerospace and automotive industries.

In parallel, the means dedicated to the verification of the procedures linked to quality and control processes, design, engineering, manufacturing, appeal to the logic of checklists, in a digital format (spreadsheet), but which are stored essentially in text form. Various checklist are used in the Product Lifecycle Management (PLM) concerning requirements, design, maintenance, etc. They are mainly characterized by the need to share information efficiently in a collaborative work and by a hierarchy of questions on a textual basis. They require in succession a navigation in the checklist, an inspection of the item and/or an experimentation of the functionality and an update of the current information concerning the item. While there is an increasingly strong need for integrated numerical tools that may be used in all the stages of the industrial Product Lifecycle Management (PLM),

the state-of-the-art studies claiming a VR-PLM integration in the literature, always focus on a particular step or aspect of the PLM. As an answer to these needs, we propose a generic tool for immersive checklist-based project reviews that applies to all steps of the PLM. It allows to link the virtual experiment of the 3D visualization and navigation, the manipulation of 3D digital models and the interactive update of an industrial checklist describing a procedure supplied by an industrial partner. So, for each of the questions listed in the checklist, the following possibilities are given to the user:

- to share with other operators or industrial sites the immersive visualization of the 3D digital model of the system to be checked;
- to interact intuitively with the 3D model in order to perform the tests listed in the checklist virtually;
- to save simulations or snapshots related to each step of the procedures listed in the checklist;
- to update the checklist (e.g. attach text comments or 3D multimedia simulations to the corresponding tests listed in the checklist).

These actions are made possible by the implementation of a virtual reality platform composed of a 3D immersive display, tools for motion capture, a haptic arm [13], a data glove [26] and a software layer allowing the implementation and the running of interactive real-time scenarios which enables the association of manipulation properties to the 3D objects stemming from a CAD model of an industrial system. The contribution is three-fold:

\* Corresponding author. Tel.: +33 05 62 44 50 80.

E-mail addresses: [Philippe.Fillatreau@enit.fr](mailto:Philippe.Fillatreau@enit.fr) (P. Fillatreau), [fourquet@enit.fr](mailto:fourquet@enit.fr) (J.-Y. Fourquet), [simon.cailhol@enit.fr](mailto:simon.cailhol@enit.fr) (S. Cailhol).

1. a generic tool for virtual experiment-based checklists that applies to all steps of the PLM.
2. the integration of various VR tools and concepts in an industrial framework.
3. a new paradigm of 3D immersive protocol for design, quality, control, engineering, etc. of industrial parts or systems, based on original gesture recognition.

In this paper, we first present a state of the art of virtual tools for industry, and the industrial context of this work. Then, we present our novel and generic VR review paradigm, focusing on VR tools for checklists and on a 3D immersive protocol based on hand posture and position recognition. Implementation details and experimental results are provided, and the paper ends with the conclusions and perspectives of this work.

## 2. State of the art of VR tools for industry

### 2.1. VR applications in general

Virtual Reality (VR), as defined in [12], is “*a scientific and technical domain exploiting the possibilities of computers and behavioural interfaces to simulate in a virtual world the behaviour of 3D entities, which interact in real time with each other and one or more users in pseudo-natural immersion through sensorimotor channels*”. The techniques of immersion in virtual reality call for different means corresponding to the user’s senses. They connect the implementation of sensorimotor interfaces to the processing of the virtual world in which the user is immersed. Thus, the operator receives information about the digital scene (3D stereo immersion using a big screen, collision force feedback through a haptic device to sense the contact with virtual objects in the environment, etc.) and he can act on this scene thanks to the implementation of driving interfaces (haptic arm, motion capture system allowing to pilot the point of view of the user or the animation of a human avatar, data glove). VR has been developing over the past few decades and has especially gained tremendous attention and developments in the last ten years. This technology has penetrated into the fields of games, health, biology, military operations, education, learning and training, etc. and given birth to applications like tele-presence and tele-operation (see [17] for tele-presence for conferences or [35] for robot tele-operation), data visualization and exploration (see [11] for immersive data visualization to help for decision making), or augmented reality (see [6] for a maintenance application in the fields of aeronautics).

### 2.2. Virtual prototype versus physical prototype

Meanwhile, the emergence during these last decades of computing technologies and more recently of tools for building digital mock-ups or 3D digitalization of existing objects has made virtual prototyping a more and more common practice in many industrial sectors. At the development stage of products, industrial companies now prefer, when applicable, exploiting digital models rather than expensive real physical prototypes. Generally, virtual prototypes are used in the upstream design steps, and real prototypes in the downstream steps.

Using such digital prototypes poses a number of questions. Choosing the type of model to be built is a critical one. Virtual prototypes usually correspond to 3D CAD models. As the prototypes to be validated become more and more complex, the corresponding 3D models and involved geometries become increasingly sophisticated. Up-to-date CAD tools also allow associating useful properties to the geometric objects involved, e.g.:

- information on which material the object is made of (often in relation to appearance through the implicit use of a textures library);
- mechanical characteristics such as modulus of rigidity, Young’s modulus, Poisson’s ratio, or friction coefficient, to be used by materials resistance or finite elements computation tools;
- appearance properties (transparency or opacity, texture);
- other physical properties like qualifying a given geometric object as an obstacle or not in 3D simulations where the objects are in motion.

Model structure is also a key question; an appropriate structure can be designed for specific tasks; a relevant organization of the model geometries into a hierarchy can be used to automatically generate nomenclatures. Last but not least, format conversions and compatibilities are another central question posed by virtual prototyping in industry, as a virtual prototype is generally processed through different tools (no integrated tool over the complete Product Lifecycle Management exists) and data often have to be shared between different industrial sites.

Physical models still are necessary at some downstream steps (for example, car industry uses sculpture clay models for designers to check the physical form of a car). But, when applicable, the use of virtual prototypes provides many advantages. Dépincé et al. [8] have listed the expected benefits of Virtual Manufacturing. From the product point of view, they emphasize reduction of time-to-market, of the number of physical prototype models, and the improvement of quality. In the design phase, listed benefits include the possibility of simulating manufacturing alternatives, to optimize the design of product and processes for specific tasks (e.g. assembly) or evaluate various production scenarios; from the production point of view, the authors emphasize the reduction of material waste and cost of tooling, the improvement of the confidence in the process, or lower manufacturing costs. Mousavi et al. [28] present a survey carried out among several international and domestic car companies of Malaysia about the benefits and barriers of using VR prototypes and systems. Emphasized benefits include reduction of rework, improvement of quality, cost savings, better client satisfaction, marketing effectiveness, and productivity, while highlighted barriers include the possible lack of trained people, the time needed to get proficient, software and hardware costs, and the lack of software and hardware standards. Thus, both studies define mainly trade-oriented qualitative impact factors for the use of VR techniques and very few numerical indicators to measure this impact are proposed in the literature. More recent works [36] emphasize other advantages of the use of VR prototypes or techniques:

- digital models make it possible to automatically generate associated documentation (e.g. nomenclature);
- virtual prototypes allow implementing multi-site remote collaborative work (involving remote users and data sharing) (see e.g. [17] for a Mixed Reality teleconference application with several remotely located users in a shared virtual world with shared virtual objects).

### 2.3. VR-PLM integration applications

As more and more powerful Computer-Aided Engineering (CAE) tools arise, there is an increasingly strong need for integrated numerical tools that may be used in all the stages of the PLM.

In a rare review of VR applications in manufacturing process simulation, Mujber et al. [29] propose a classification for VR applications in industry into three groups: design (design and prototyping), operations management (planning, simulation and training) and manufacturing processes (machining, assembly,

inspection). Although this demonstrates a wide range of industrial applications for VR, the use of VR is far from reaching all stages of the PLM (products requirements validation and acceptance of product, for example, are not really addressed by VR applications).

As a matter of fact, if we look at studies claiming a VR-PLM integration in the literature, they always focus on a particular stage or aspect and we can distinguish works dealing with:

- assembly or disassembly applications: Bordegoni et al. [3] involve two 6-DOF interfaces (a haptic device and a Wiimote control). Li et al. [21] propose VR tools for disassembly and maintenance training, the disassembly actions sequence being automatically generated from the assembled geometries describing the system to be operated. Look and Schomer [22] focus on the modelling of rigid and deformable objects for assembly simulations.
- ergonomics analysis: Moreau et al. [27] deal with the design of a haptic device to study the ergonomics of a push button, [32] with the modelling and animation of virtual hands for the manipulation of 3D objects using a haptic interface. Di Gironimo et al. [9] present an innovative methodology for assessing the usability of a product, focusing on the definition of a synthetic usability index. Marc et al. [24] show how virtual reality can be a tool for a better consideration of the usability of a product, highlighting the contributions of engineering and psychoergonomic approaches to integrate health and safety from the design stage on. Chedmail et al. [5] present a multi-agent architecture to validate a path planner for a manikin or a manipulator robot for access and visibility tasks and to allow the user to take into account (among other things) ergonomic constraints for the manikin or joints and mechanical limits for the robot. More generally, ergonomic requirements are often expressed in a checklist (see for example [14] or [1]) and can take advantage of VR techniques.
- Product modelling: Bordegoni et al. [2] deal with the development of a VR application and a haptic interface intended for designers or sculptors; the development is based on the observation of professional designers while modelling to reproduce in the virtual world the modelling techniques used in the real world; Bourdot et al. [4] and Picon [31] deal with the integration of classical CAD modelling techniques in VR, enriched by haptic feedback. Meyrueis et al. [25] define and use the D3 procedure for immersive design: (1) Draw (selection of surfaces to be modified), (2) Deform (definition and making of modifications), (3) Design (transfer of modifications made to the CAD models). Raposo et al. [33] integrate VR and CAD in engineering (maintenance) projects for large complex petroleum engineering projects. Further works propose approaches for coupling VR and PLM systems by reducing the authoring burden, like Noon et al. [30] (rapid design and assessment of large vehicles) or Makris et al. [23] (involving semantic-based taxonomy for immersive product design).
- Simulation: Dangelmaier et al. [7] use VR and augmented reality techniques for manufacturing processes, and propose a generic solution for user interface and data structure, and Lee et al. [20] involve augmented reality for workshop design and update simulations.
- Decision-making help: Dijkstra and Timmermans [10] develop a research tool for conjoint analysis i.e. analysis of parameters having an influence on a consumer's decision to buy a product. Eddy and Lewis [11] propose a *cloud representation* of data for decision-making help. Kieferl et al. [18] use Virtual and Augmented Reality for project planning in architecture or urbanism.

#### 2.4. VR-PLM: synthesis and challenges

VR is now used in many industrial applications and cuts costs during the implementation of a PLM. The main challenges are a result of the following drawbacks:

- implementation of a CAE simulation is a time-consuming process;
- VR systems used in industry focus on one or a few particular steps of a development cycle (e.g. design review), and may be used in the framework of the corresponding product development project review. There is no VR tool in the current state of the art which enables us to deal globally with the different steps of the PLM and the corresponding projects reviews.

The work presented here can bring an improvement with respect to these commonly encountered drawbacks. It aims at proposing an integrated multimodal VR project review tool. The benefits of this tool in the PLM will be threefold:

- first, it constitutes a generic project review tool which may be used for any project review in the PLM: only the virtual experiments differ and the project review script we developed only needs to involve the right experiment-oriented simulation module. This will allow a drastic reduction of development times for project review simulations;
- second, its multimodality enables us to produce multimedia documents associated with the whole PLM (not only project reviews but also virtual prototypes, or scenarios and reports for products or systems operation simulation);
- third, the proposed project review paradigm will offer rich interaction and immersion means, as it may use any of the VR simulation modules integrated in our platform.

### 3. Industrial context

The works presented here have been developed in partnership with a transportation company. In this domain, products or systems are complex and arise from the integration of various components, which involve different competences: mechanical design, sizing of electric actuators and converters, adaptation of air/water cooling systems, etc.

In order to develop such complex products or systems, a global scheme indicating the different steps of the PLM, together with the associated gate reviews has been developed, allowing for a step by step checking. The gate reviews are usually described as a list of questions to be answered; some of them may need to perform some experiments (for example, checking the presence of a specific part or system at the design stage, or verifying the operation of a system to simulate operations at assembly or maintenance stages).

The PLM approach intends to provide, among other things, traceability between PLM steps, the ability to detect errors as early as possible, therefore to anticipate potential errors before future steps are reached. For example, at a given system design phase, an exhaustive verification of the design should also provide a way to validate future operations of the system, e.g. assembly or maintenance. The numerous questions to be answered and tests to be performed during a given project gate review are usually gathered in checklists. These checklists are generally made up of worksheets that should be updated textually by integrating the results obtained for each question set or test to be performed.

To perform these tests using traditional methods, industry needs to build various physical prototypes of the parts or systems to be produced, and a physical manipulation of the real components is often required. Review checklists then allow exhaustive tests needed to validate any stage of the PLM, from the requirements, to the design and compatibility of system components, to the final assembly, operation and maintenance. Note that the way the experiments are performed on the real prototype is generally not memorized or linked to the updated checklist.

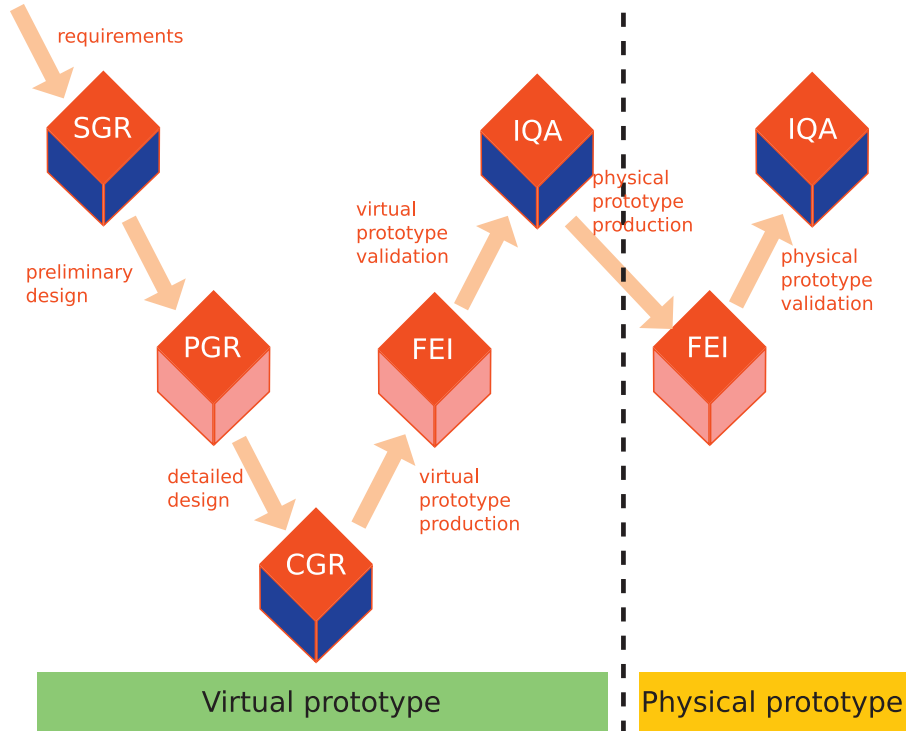


Fig. 1. A VR-adapted product development cycle.

Now, CAD models are progressively integrated into PLM software suites. Industrial companies aim at running as many of the project review checklists as possible using virtual numerical models of the parts or systems and their components instead of a real prototype, in order to optimize development costs. Fig. 1 inspired from Alstom Transport's product development philosophy shows a product or system development cycle. It presents the main development steps, and the associated gate reviews (red diamond-shaped boxes at the passage from a given project step to the following one): the SGR (Specification Gate Review) is the requirements review; the PGR (Preliminary Gate Review), is the preliminary design review; the CGR (Critical Gate Review) is the detailed design review; the FEI (First Equipment Inspection) is the prototype review; and the IQA (Initial Quality Approval) is the industrialization review. Fig. 1 shows how the industrial companies intend to use virtual prototypes to check as many steps as possible. Only the steps that cannot be performed without a physical prototype should involve a real prototype.

However, many project reviews require experimentation (i.e. manipulation or operation of parts or systems), and building and running the corresponding simulations remains a difficult task as the state of the art presented in Section 2 shows. It requires simultaneously visualizing and manipulating the corresponding 3D components or systems in a realistic and intuitive way. The increasingly powerful immersive capabilities of VR tools open the way to new possibilities of performing checklist tests in VR, by using more and more off the shelf or specially tailored interactive means on virtual prototypes.

#### 4. A generic VR project review paradigm

Our contribution relies on the digital model of an electrical power converter. The virtual world is thus constituted by a workshop in which the operator can act on the various 3D digital components of the converter designed by the engineering

department of the company. This 3D environment is placed in the background of a given checklist usually used by the company for a project review (e.g. a product design review). Thus, every item of this checklist is dynamically connected to a scene in which a certain number of actions are made available to the user. The user can move in the scene thanks to the motion capture of markers he is wearing. He can also adapt his point of view of the scene thanks to the motion capture of his 3D glasses. For object manipulation, the chosen mode of interaction rests on the simultaneous use of a data glove, which enables us to measure the position of the various fingers of the operator's hand, and of the optical motion capture of a frame attached to the operator's hand equipped with markers. These two pieces of information are used to navigate in the scene, seize objects, visualize the avatar of the hand of the user but also to navigate through the interactive menu of the checklist in order to update it (e.g. attach multimedia information about the tests performed). The simultaneous detection of the postures of the hand (relative positioning of fingers) and of the hand trajectories allows a large variety of intuitive means of interactions and constitutes an original scientific contribution of this work.

To meet our objectives, we integrated the Alstom checklist (encompassing all the steps and gate reviews related to a given project) to our VR platform. We created a VR checklist paradigm which aims at running any gate review of an industrial project, using all the basic modules scripts already developed in our VR platform, e.g. interactive planning for systems assembly or disassembly [19], parts manipulation using haptics or cyberglove devices, virtual visit or inspection using motion capture or a haptic device, human movement generation, motion capture and analysis [15], etc.

##### 4.1. Integration of various VR modules and concepts in an industrial framework

A VR environment must provide the operator with the ability to execute a multiplicity of scenarios by using 3D and multimedia

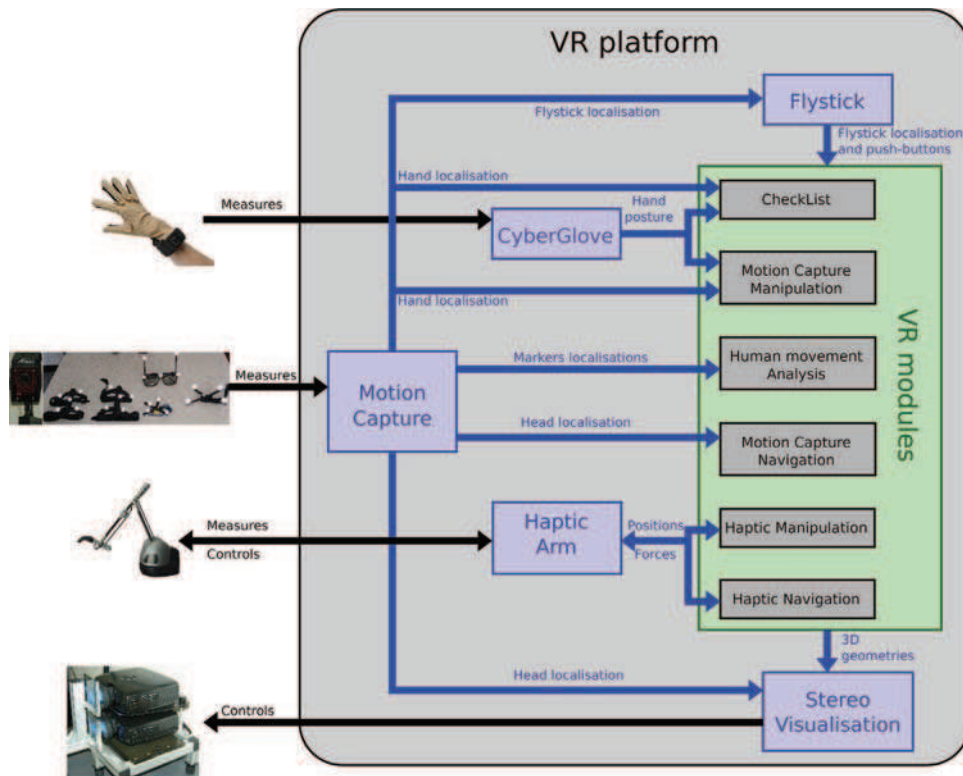


Fig. 2. VR simulation structure (for interpretation of the references to colour in this figure, the reader is referred to the web version of the article).

contents through sensorimotor devices. In order to realize the global integration of the multimodal checklist VR module and of all other modules and devices on our VR platform, we have designed the modular architecture presented in Fig. 2. Thus, the project review simulation environment is based on:

- devices: a set of sensorimotor interfaces and their controllers (blue boxes in Fig. 2): data glove, IR motion capture, flystick, haptic arm, stereo visualization.

- modules: a set of VR modules (grey boxes in the green box) corresponding to independent scripts. “Checklist” enables us to open a review checklist file, to explore all corresponding procedures and integrate answers to the corresponding questions. “Motion Capture Manipulation” enables us to use the data glove and the motion capture systems to manipulate objects. “Human Movement Analysis” allows for human movement generation, motion capture and analysis. “Motion Capture Navigation” enables us to navigate (e.g. visit or explore the scene or inspect objects) in the virtual scene using the motion capture system. “Haptic Manipulation” and “Haptic Navigation” correspond respectively to object manipulation and navigation in the virtual scene using the haptic arm.

- data flows: Starting the simulation script triggers all VR modules, which keep running in parallel. All device controllers are also started in parallel, so each device integrated in the platform is also ready for use. Fig. 2 also describes the data exchanged between all involved modules, and the direction in which the data is exchanged. The black arrows describe the data exchange between each device and its controller; the blue arrows describe, the data exchanges between the device controllers and the VR modules. The data exchanged between the devices and their controllers are basically measures and/or control signals; the data exchanges between the device controllers and the VR modules are linked to the nature of the devices and the interaction and immersion possibilities they offer. For example:

- the “Checklist” VR module specifically uses a combination of 3D pose (position and orientation) of a markers-based target attached to the data glove and hand configuration (provided by the 22 sensors of the data glove), according to the hand posture and pose paradigm presented in Section 4.3. These data are respectively provided by the motion capture system and the data glove.
- the data exchange between the haptic device and the “Haptic Manipulation” and “Haptic Navigation” VR modules is bidirectional and data exchanged consists mainly of the position and orientation of the end-effector of the haptic arm.

Fig. 2 also shows that the stereo visualization and the flystick systems are used by all VR modules. The stereo visualization module uses of course the 3D geometries of the objects of the scene, but also the localization of the head supplied by the motion capture system in order to control the point of view in the scene (see Section 6 for further details).

#### 4.2. A generic VR tool for checklists

What we have mainly developed in this work is a generic tool for project reviews that has been tested by running the associated checklists and virtual experiments through all the steps of the PLM. Fig. 3 presents the advantages of this tool and its ability to bring improvements to all steps of the PLM.

VR simulations of project reviews use the VR modules and devices integrated in our VR platform. For each step of the PLM, our tool allows the users:

- to run a number of VR modules and VR devices to perform virtual tests and experiments associated with this step.
- to generate multimedia documentation associated with the corresponding review.

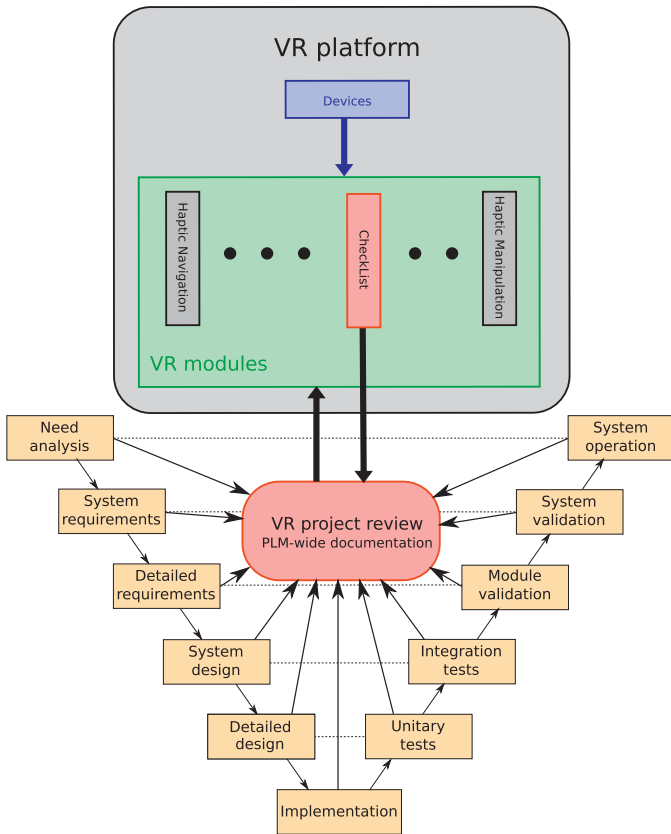


Fig. 3. PLM conception cycle with VR tools.

To be more precise, this tool allows the user to open the checklist, explore the whole set of questions, perform the virtual tests, and update the checklist by attaching multimedia information such as: text information to answer a question (by using a standard computer keyboard), screenshot of a view of the system or part to be controlled (to prove the presence of some desired feature for example), video recording of a virtual test (by using the standard possibilities offered by Virtools). The attachment of multimedia information to the check-list file is made available to the user through a specific menu (as shown in video 2, figure 11, (2 : 13)).

The implementation of the project review itself and the way devices or VR modules are run are the same for each PLM step. The only components related to each particular PLM step are the answers given to the questions and the virtual experiments performed. Scripts allowing to run the given VR modules are modular and fully reusable in any virtual experiment performed. This feature allows us to obtain short development times of project review simulations and thus gives an efficient solution to one of the main limitations of the current CAE state of the art presented in Section 2.4.

The expected added value lies in the economical (saving of cost and time) and environmental (virtual versus real prototype) advantages of the use of virtual prototyping over the whole PLM, as well as quality management benefits (problems can be better anticipated and errors are detected earlier in the PLM) leading to more preventive and fewer corrective actions.

#### 4.3. 3D immersive protocol based on hand posture and position recognition

The development of the Checklist module has given rise to a new 3D interactive protocol to explore the checklist architecture



Fig. 4. Used hand postures for Checklist navigation.

by using hand gestures. The principle relies on the joint use of 2 types of information:

- Detection of hand postures, measured by the data glove, among a predefined set of significant hand postures. Fig. 4 shows the alphabet of postures we used in this work for the checklist.
- Detection of hand movements, using the IR motion capture system and a target equipped with retroreflective markers.

The combination of those 2 pieces of information allows recognizing actual hand postures and gestures in order to explore the checklist and to perform virtual experiments.

The checklist data is represented as a tree structure illustrated in Fig. 5. In this example, level 1 defines the gate review type (requirements, design, etc.) and level 2 defines the main technical domains (electrical, mechanical, etc.). The following levels identify subdomains, if any (the number of levels may vary depending on the checklist considered), and the tree leaves correspond to the questions and tests to be performed. Fig. 5 also presents the hand postures or movements to be used to explore the tree: hand posture 1 to move from level  $n$  to level  $n + 1$ , posture 2 to move from level  $n$  to level  $n - 1$ , hand posture 3 associated with motion capture allows selecting one item, and hand posture 4 associated with motion capture allows vertical scrolling of a set of items in order to reach a non displayed item. These postures enable the user to navigate and select items inside the tree structure of the

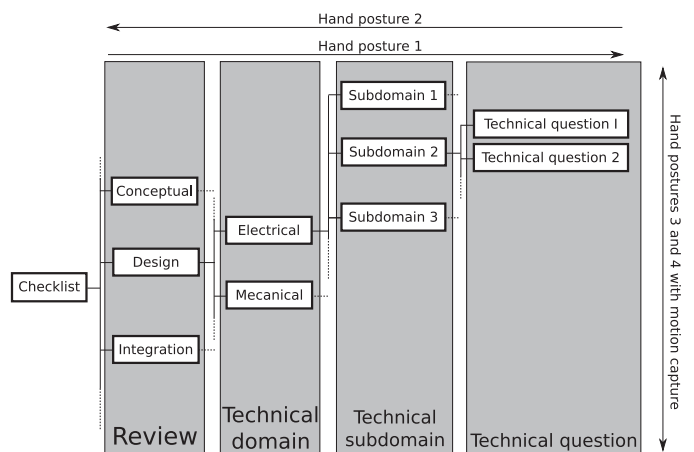


Fig. 5. Checklist tree structure.



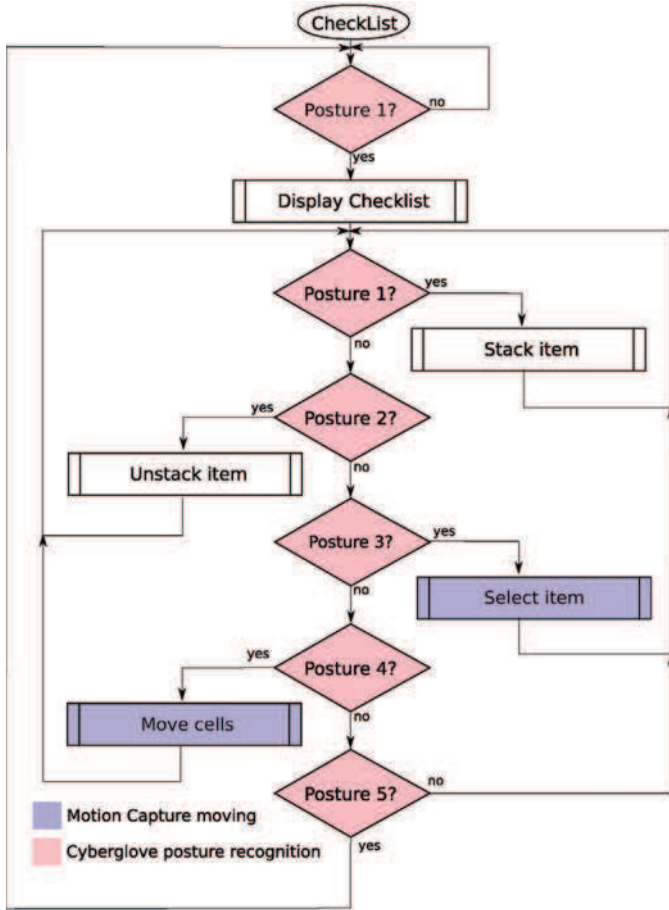


Fig. 6. Checklist algorithm.

checklist. Finally, postures 1 and 5 allow the user to respectively enter and quit the checklist exploration.

Fig. 6 presents the complete algorithm of the Checklist module.

Posture recognition is based on a metric related to the angles measured on the 22 sensors provided by the data glove. At the beginning of each checklist simulation, a vector of sensor values for a neutral posture  $P_n$  is recorded and the user is asked to perform a 30 s initialization procedure. This procedure records vectors of sensor values associated with postures 1–5. A signed and normalized distance  $P_{ij}$  to neutral value is computed for each sensor  $j$  and each reference posture  $P_i$ :

$$P_{ij} = \frac{v_{ij} - v_{nj}}{UB_j - LB_j}$$

where  $j$  is the sensor index,  $v_{ij}$  the measured value for posture  $i$  and sensor  $j$ ,  $v_{nj}$  the measured value on sensor  $j$  for the neutral posture,  $UB_j$  and  $LB_j$  are respectively the upper and lower bound on sensor  $j$  values. Then, the posture recognition module compares these distances to the distance between current and neutral posture  $P_n$ :

$$d_i = \sqrt{\sum_{j=1}^{22} \alpha_j^2 (P_{ij})^2}$$

where  $\alpha_j$  is the tuned weight that permits efficient identification of postures. Then a current posture  $P$  is recognized as one of the 5 specific postures  $P_i$  of the figure 4.3 when the distance  $d_i$  is lower than a predefined threshold  $\epsilon$ . This simple tuning method is

efficient in the considered framework and can be compared with results in the literature (e.g. [26]).

In fact, on the one hand, IR captured situation of the frame attached to the hand enables the operator to navigate geometrically in the virtual scene, to navigate in the checklist menu and, on the other hand, the data glove enables the operator to select and to navigate hierarchically in the menu but also, when the virtual experiment is running, to perform specific operations: catching or pushing objects in the virtual experiment. The avatar of the hand appears on the virtual scene in order to show relative positioning in space but also to show actions. As a conclusion, the joint use of the motion capture and dataglove for hand posture and position recognition allows the interacting user to be autonomous and effective in capitalizing data during the simulation in the VR environment.

Obviously, the navigation and selection protocol could be adapted depending on the sensorimotor interfaces without significant changes to the global architecture of the VR environment.

## 5. Implementation

The above approach has been implemented by using specific devices and software in order to explore feasibility and to quantify the benefits of this new project review environment. Of course, other technological choices remain consistent with the approach.

### 5.1. The VR platform hardware

In this section, we present the VR platform of the laboratory (see Fig. 7). It consists of the following elements:

- A passive stereovision 3D immersive visualization system composed of the following items: two ProjectionDesign F2 video projectors fitted with two optical filters allowing for a circular polarization of the light, a 3 m high and 2.25 m wide stereo screen, several pairs of 3D glasses adapted to the passive visualization thanks to equally circularly polarized glasses.
- A “Virtuose 6D 35-45” haptic arm (see Fig. 8). The haptic system is composed of two elements: a “Virtuose 6D 35-45” haptic arm and a control PC. The haptic arm is a sensorimotor bidirectional interface which allows manipulation by the user and force feedback.
- A “CyberGlove II” wireless motion capture data glove (see Fig. 8), which uses proprietary resistive bend-sensing technology to provide in real time 22 joint-angle measurements (thus providing real-time measurements of the hand posture configurations).



Fig. 7. VR platform.



**Fig. 8.** Sensorimotor interfaces: haptic arm on the left, head and hand ART markers, cyberglove.

- An ARTrack<sup>®</sup> Infrared (IR) motion capture system (see Figs. 7 and 8). The system designed by the ART company, is composed of four IR cameras, six sets of targets, each bearing a set of passive retroreflective markers set-up in a distinctive geometric configuration, and a control PC. It provides in real time the 3D position and orientation of any target. The operator can also use a controller named *flystick*, allowing him to communicate orders corresponding to actions on the flystick buttons, including a two analog axis control, and equipped with markers for localization by the motion capture system.

### 5.2. The VR platform software

The main software components are:

**CAD:** The virtual environments manipulated and explored are based on 3D CAD models generated with standard CAD tools.

**Virtools:** All modules presented in this work (project review and VR modules) have been implemented as scripts using the Virtools<sup>®</sup> environment for interactive simulations development. The three levels of development provided by Virtools have been used:

- Level 1: Top graphical level (data flow type graphical scripts, involving behavioural processing blocks called Building Blocks (BB)).
- Level 2: VSL (Virtools Scripting Language) that allows the programmer to build specially tailored BBs.
- Level 3: C language level (SDK). This level has been used notably for computations needing more advanced memory management.

Virtools is used to endow CAD objects with properties used in interactive simulations. In particular, Virtools associates behaviour properties – or attributes – with the 3D objects manipulated such as: being an obstacle or not, being mobile or not. It also endows CAD objects with physical properties (defining gravity, deformation of objects) and builds hierarchies between objects.

**Microsoft office suite:** The checklist has been written as an excel worksheet. This format serves as input/output storage format.

### 5.3. Running the Checklist module

The Checklist module opens the excel file, imports data and builds the corresponding tree architecture in the Virtools environment. Then, the different levels of the tree are displayed as interactive menus and are accessible together with their content through the gesture recognition system. When a question is selected, the associated 3D virtual environment is launched and the operator executes the virtual experiment with a wide range of scenarios. During the virtual experiment, the operator can start video or snapshot recording. When a question has been checked, an answer is stored in the excel spreadsheet and linked dynamically to the multimedia data related to the virtual experiment (videos, snapshots).

## 6. Experimental results

The checklist tool has been implemented and tested on the laboratory VR platform. The videos in this section show the experiments.

The first video (Fig. 9) illustrates the use of the gesture recognition system for checklist navigation. First, the hand posture calibration procedure that builds the alphabet is shown. Next, each navigation functionality in the checklist tree structure is used (posture 1 to validate an item or a question, posture 2 to step back in the checklist tree structure and postures 3 and 4 with motion capture to respectively select and scroll items). In this video, posture 1 is also used to open the checklist, and posture 5 to close it.

In the second video (Fig. 10), the checklist is performed to answer two technical questions. In this video, part manipulation is done thanks to cyberglove and motion capture and the hand's avatar is displayed in the scene. The first technical question is selected and answered by using a snapshot of an inspected part. A new technical question is then selected and answered by recording a video showing part assembly thanks to the cyberglove and motion capture manipulation.

The last video (Fig. 11) illustrates the use of checklist and haptic manipulation modules together. First, a technical question is selected in the checklist, then, a video of the test is recorded. To complete the multimedia documentation of the technical question, a comment is typed. The technical question is set as “seen” and we can further see the checklist spreadsheet updated.

Preliminary feasibility experiments have been conducted with about ten engineers. They prove the usefulness of the approach and the quick adaptation of the user to the navigation and selection scheme. In particular, the selected procedure for calibration is



**Fig. 9.** Checklist navigation [video1.mp4].

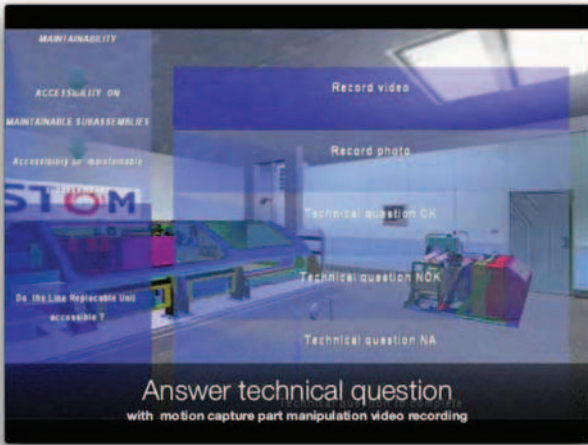


Fig. 10. Checklist and motion capture navigation and manipulation [video2.mp4].

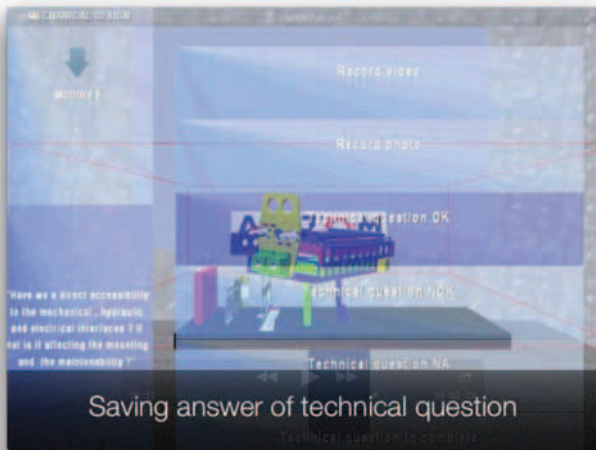


Fig. 11. Checklist and haptic manipulation modules [video3.mp4].

successful and is not really sensitive to user change. It takes between 15 and 30 s depending on the skill of the user. Then, after this calibration phase, the engineers succeeded in naturally moving around inside the checklist and selecting items in the menu. The hand posture recognition is not sensitive to user change thanks to the initialization procedure at the beginning of simulations. Concerning robustness issues when facing a large number of users, it could be interesting to study the reduction of the size of the posture alphabet. A smaller posture alphabet can be obtained by using more motion capture (for example, we could use horizontal movements to change menu levels in the checklist).

Concerning performance metrics, according to Section 2.2, there are currently very few numerical indicators to measure the impact factor of this kind of approach in the literature, and the measure of this impact can only be done through mid-term evaluation by the (industrial) end users.

## 7. Conclusion and perspectives

A new paradigm for 3D immersive project review has been developed on a modular basis by using a VR environment. It has been tested successfully for feasibility on a real industrial product

development case and is naturally adapted to a variety of situations involving checklists (e.g. assessment of a new maintenance procedure, upgrade of a product, reorganization of a factory, etc.).

This work does not claim to provide a commercial tool. It provides a proof-of-concept of a new way of using numerical data and interactive simulation in a widespread industrial procedure. This work explores how companies could improve significantly the traceability of project reviews, decisions and documentation in all the steps of the PLM.

The modularity of the architecture is such that other means of interaction are conceivable without drastic changes of the whole scheme. New interactive means are easily “pluggable” into the architecture depending on their increasing efficiency: in particular, keyboard typing of answers will be beneficially replaced by speech recognition tools. This paves the way towards a hand-free collaborative checklist based on virtual experiments with the ability to store numerical data relative to questions and to experimental procedure.

Preliminary feasibility experiments have been conducted with engineers. They prove the usefulness of the approach and the quick adaptation of the user to the navigation and selection scheme. The engineers who have tested the proposed tool predict improvements over the conventional methods. Now, the assessment of those benefits would now require mid-term experiments by the industrial end users. Of course, the key to a wide and professional dissemination of this approach is the ergonomics of the entire 3D environment from both software and hardware viewpoints.

## Appendix A. Supplementary Data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.compind.2013.03.018>.

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**P. Fillatreau** graduated from the ENSEIHT Engineering School in 1988. He obtained his PhD in perception for mobile robotics in 1994 at the LAAS-CNRS Laboratory, Toulouse, France. His PhD works, funded by the Framatome Company, dealt with perception, 3D environment modelling and localization for an autonomous all-terrain mobile robot, in the framework of joint projects dealing with public safety or planetary exploration. In 1991–92 he spent one year at the Matra Marconi Space (now Astrium) Company, where he was involved in the Eureka-AMR project. In 1994–95, he was a post-doctoral visiting researcher at the Department of Artificial Intelligence of the University of Edinburgh, Scotland; funded by a Human Capital and

Mobility fellowship of the European Community, his works dealt with non polyhedral objects recognition and model update for public safety mobile robots. In 1996, Philippe Fillatreau joined the Delta Technologies Sud-Ouest Company

(Toulouse) where he was technical head of the computer vision activities. There, he lead research projects in the fields of Computer Vision and Algorithm Architecture Adequacy, aiming at integrating advanced image processing algorithms in smart cameras based on FPGAs for very high throughput applications (e.g. transports safety, online satellite images processing or quality control of industrial processes). In 2009, he joined the Ecole Nationale d'Ingénieurs de Tarbes as a researcher and lecturer. His current research interests are related to Virtual Reality, Computer Vision, Mobile Robotics and Algorithm Architecture Adequacy.



**J.-Y. Fourquet** received the PhD degree in robotics from the University of Toulouse, Toulouse, France, in 1990. He is currently a Professor with the National School of Engineers in Tarbes (ENIT), University of Toulouse, where, since 2011, he has been the Head of Laboratoire Génie de Production (LGP). From 1991 to 1992, he was an Associate Professor with the Computing and Systems Engineering Program, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil. From 1992 to 2000, he was an Associate Professor with the University of Toulouse and a Researcher with the Laboratory for Analysis and Architecture of Systems. In 2000, he joined the LGP-ENIT, where he led the Intelligent Manufacturing Group from 2007 to 2009 and the Dynamic Decision and Interactions for Systems team from 2009 to 2011. He has participated or led various projects at the industrial, regional, national, or European levels. His research interests mainly concern mobile manipulation, human motion simulation, and interactive assembly scenarios.



**R. Le Bolloc'h** graduated from the ENIT Engineering School (University of Toulouse, France) in 2011. His works lead during his five months internship ending his studies at the ENIT and a six months follow-up research contract at the LGP-ENIT laboratory dealt with interactive and immersive project reviews based on checklists, and were supervised by Philippe Fillatreau and Jean-Yves Fourquet. Romain continued his career developing various mobile GPS and mapping applications on Android OS, and has recently joined Accenture Technology Solutions in Singapore as associate software engineer.



**S. Cailhol** graduated from the ENIT Engineering School (Université de Toulouse, France) in 2011. To finish his studies at the ENIT, he made his five months internship in the LAPLACE (Laboratoire PLASma et Conversion d'Énergie) Laboratory of the ENSEIHT Engineering School in Toulouse where he worked on a mathematical approach for pulse width modulation. In September 2011, he integrated the DIDS (Décision et Interaction Dynamique pour les Systèmes) team in the LGP (Laboratoire de Génie de Production) Laboratory of the ENIT Engineering School as a PhD student to work on interactive path planning on the VR platform of the laboratory under the supervision of Jean-Yves Fourquet and Philippe Fillatreau.



**A. Datas** graduated from the ENIT Engineering School (Université de Toulouse, France) in 2008. To finish his studies at the ENIT, he made his five months internship at the IRCcYN (Institut de Recherche en Communications et Cybernétique de Nantes) in Nantes where he worked on biped locomotion. In September 2008, he integrated the DIDS (Décision et Interaction Dynamique pour les Systèmes) team in the LGP (Laboratoire de Génie de Production) Laboratory of the ENIT Engineering School as a PhD student to work on human motion under the supervision of Pascale Chiron and Jean-Yves Fourquet.



**B. Puel** received French diploma of Engineering from National School of Engineers in Tarbes (ENIT) France, in 1986. He is currently Senior Expert in Traction and Auxiliary Electronic Converter Hard ware in Alstom Company on railway equipment's associating Tarbes, Charleroi and Milan Traction network sites. He created and animated different Mechanical Integration design offices in Tarbes as Electronic Power module hardware for all Alstom Transport in 1997, Traction and Auxiliary Converters in 2007. He has participated or led various projects on internal Alstom developments, patents and supervising of thesis work relating to Mechanical fittings & Structural Glue on Traction & Aux cubicles from 2005 to 2008, Virtual Reality about Design, Maintenance and Industrialization from 2008 to 2011.