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INTEGRATING VIRTUAL REALITY FOR VIRTUAL PROTOTYPING

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ABSTRACT

Business process re-engineering is becoming a main focus in today's efforts to overcome problems and deficits in the automotive and aerospace industries (e.g., integration in international markets, product complexity, increasing number of product variants, reduction in product development time and cost).

In this paper, we investigate the steps needed to apply virtual reality (VR) for virtual prototyping (VP) to verify assembly and maintenance processes. After a review of today's business process in vehicle prototyping, we discuss CAD-VR data integration and identify new requirements for design quality. We present several new interaction paradigms so that engineers and designers can experiment naturally with the prototype.

Finally, some results of a user survey performed at BMW are presented, showing the acceptance and feasability of VP and the paradigms implemented for our key process. The results show that VR will play an important role for VP in the near future.

Keywords: Virtual environments, virtual prototyping, digital mock-ups, assembly and maintenance process, user acceptance, direct manipulation.

1 INTRODUCTION

Markets are becoming more and more dynamic and quick-paced. In order to stay competitive, companies must deliver new products with higher quality in a shorter time. Additionally, they must provide customers with a broader variety of versions at minimum costs. Therefore, rapid prototyping and virtual prototyping (VP) are quickly becoming interesting tools for product development.

Automotive industries seem to be among the leaders in applying virtual reality (VR) for real-world, non-trivial problems. After all, this is only natural, since they have been also among the first who applied computer graphics.

While some automotive companies have already begun to routinely use VR as a tool in styling and design reviews in the concept phase, it has not been clear that VR can be an efficient tool in assembly/disassembly simulations and maintenance verifications. Assembly simulations are much more difficult in that they involve a lot of interaction and real-time simulation. However, Boothroyd and Dewhurst (1983) revealed that the assembly process often drives the majority of the cost of a product. Pratt (1995), Ullman (1992) point out that up to 70% of the total life cycle costs of a product are committed by decisions made in the early stages of design.

Although there are already several commercial 3D engineering tools for digital mock-up (and the number continues to grow), all of them lack one thing: intuitive direct manipulation of the digital mock-up by the human. Therefore, they are inherently inferior to VR.

Definitions of virtual prototyping. There seem to be two different understandings of what exactly VP is: the "computer graphics" and the "mechanical engineering" point of view[1].

[1] Actually, the term "virtual prototyping" is also used in other areas such as VLSI chip design.

In the *computer graphics definition* of virtual prototyping (VP_{CG}) is the application of virtual reality for prototyping physical mock-ups (PMUs). The VR system simulates and renders all characteristics relevant to the particular context as precise and realistic as possible in an immersive environment.

In the *mechanical engineering definition* of virtual prototyping (VP_{ME}), the idea is to replace physical mock-ups by software prototypes. This includes also all kinds of geometrical and functional simulations, whether or not involving humans.

Digital mock-up (DMU) is a realistic computer simulation of a product with the capability of all required functionalities from design/engineering, manufacturing, product service, up to maintenance and product recycling (Dai & Reindl, 1996).

So, immersive virtual prototyping is but one technique for implementing the DMU strategy:

$VP_{CG} \subset VP_{ME} \subset DMU$

Assembly/disassembly verification has several goals. The final goal, of course, is the *assertion* that a part or component can be assembled by a human worker, and that it can be disassembled later-on for service and maintenance. However, other questions need to be adressed, too: is it "difficult" or "easy" to assemble/disassemble a part? How long does it take? How stressful is it in terms of ergonomics? Is there enough room for tools?

2 RELATED WORK

A lot of development for utilizing VR for VP is being realized by automotive and aerospace companies. Many efforts, however, are still feasability studies.

Practically all automotive companies investigate the use of VR for styling reviews and other mere walk-through applications. Some of them already employ it for daily work. Usually, the model is rendered on a large-screen stereo projection or a cave. Variations can be compared on the fly with realistic colors and illuminations effects (Flanagan & Earnshaw, 1997). At Daimler Benz the body of a car can be reviewed in an immersive VE by the aid of zebra lighting (Buck, 1998).

Since VR provides an intuitive and immersive human-computer interface, it is perfectly suited to do ergonomics studies. Consequently, many projects capitalize on this advantage over VR. Ford employs virtual prototypes with several proposed dashboard configurations to verify instrument and visibility.

Researchers at Caterpillar Inc. use VR to improve the design process for heavy equipment. Their system (Lehner & DeFanti, 1997) allows them to quickly prototype wheel loader and backhoe loader designs to perform visibility assessment of the new design in a collaborate virtual environment. Further the engineers can simulate the operation of the equipment and evaluate visual obstructions.

Volkswagen incorporated already some useful applications in the vehicle development process. They use an ergonomic software dummy within VR to investigate different ergonomic features. They also looked at interactively visualizing the results of FEA crash computations in VR. The virtual product clinic avoids faulty developments and helps assess customers' wishes (Purschke et al., 1998).

Chrysler launched a project to study the process of virtual prototyping, to investigate the steps required for the creation of a virtual representation from CAD models, and for the subsequent use of the prototype in immersive VR (Flanagan & Earnshaw, 1997).

A vision of virtual prototyping was developed within the ESPRIT project AIT (Advanced Information Technologies in Design and Manufacturing; Project partners were many European automotive, aerospace, IT suppliers, and academia) (Dai & Reindl, 1996). A lot of visionary prototypes have been presented also by (Astheimer et al., 1995).

3 ASSEMBLY PROCESSES IN THE AUTOMOTIVE BUSINESS PROCESS

Today's computer-aided (CAx) tools for automotive and other industries can simulate a lot of the functions and operating conditions of a new product. In some cases, software simulations are as good or even better than physical mock-ups(PMUs). However, they still do not meet all requirements to avoid PMUs completely. Certain functions of a new product cannot be simulated at all by current CAx tools, while others don't provide the results in an acceptable time.

Therefore, many PMUs are built during the development process to achieve a 100% verification of the *geometry*, the *functions*, and the *processes* of a new car project. Additionally, today's CAx tools do not provide a natural and intuitive man-machine interface that allows the user to *feel* and to get the *spatial presence* of the virtual product.

In order to "fill" these gaps, many automotive and other companies have established projects to investigate the use of VR technologies for verification of designs and processes (Gomes de Sá & Baacke, 1998).

Today's approach The automotive business process chain comprises various key-processes from the early concept phase through final service, maintenance and recycling. Those that will be highlighted in this paper are the *assembly* and *maintenance* processes. The verification process can be broken down into three sub-processes which are described in the following (see Figure 1):

- *Fast CA loops.* CAx tools are used to quickly verify different design concepts and assembly/disassembly of the design concepts. These verifications take place in-between the design and the CA prototype process (see Figure 1). At the beginning of the business process chain the freedom to change

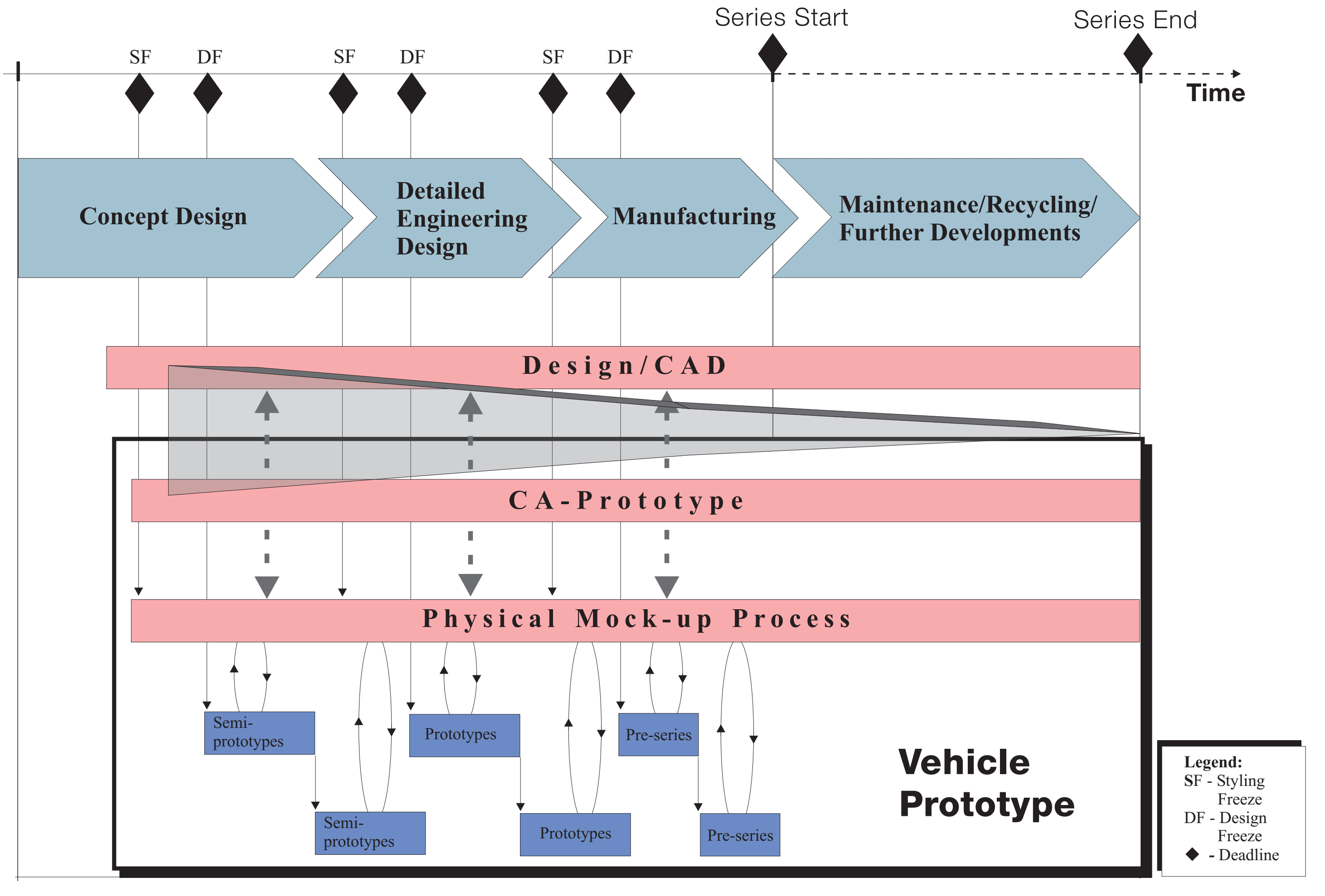

Figure 1. Process chain for the vehicle prototype activities.

concepts and the number of variations of a component is higher. Due to this fact the number of CA verifications during the development process will decrease.

- *PMU loops*. For detail verification of design concepts and assembly processes in some sections of a product, various PMUs are built. This sub-process can be identified in Figure 1 between the design and the physical mock-up process (see dashed line).
- *PMU verification*. Some complete PMUs of the final product (e.g., a car) are built to verify if all the designed components fulfil all the requirements related to *ergonomics*, *functions* and *processes*. Before these full prototypes are built, a freeze of the styling and design processes occurs. In Figure 1 these phases are marked by the deadlines SF and DF.

In these traditional process chain several problems arise due to the fact that the verification of the processes are made using PMUs and CAx tools:

- *Parallel verification processes*. Verifications are made with CAx tools and with PMUs (in this case they are obtained mostly by the use of rapid prototype techniques) concurrently. The correlation between this two verification processes is very hard to obtain.
- *Not enough co-ordination*. The handling, synchronisation, correlation, and management of these processes is very difficult and in same cases impossible. In order to build a PMU a design stage needs to be freezed. At this time, the building of the PMU starts and can take 6 to 12 weeks. Due to concurrent engineering, further changes of CAD parts (sometimes

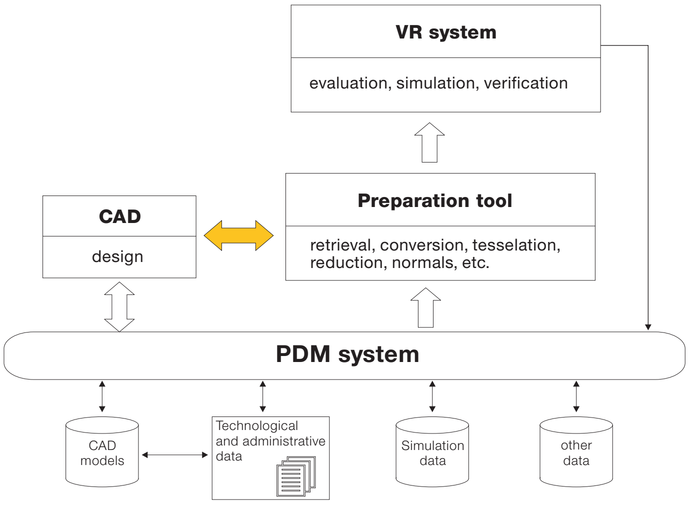

Figure 2. Data flow between CAD and VR system.

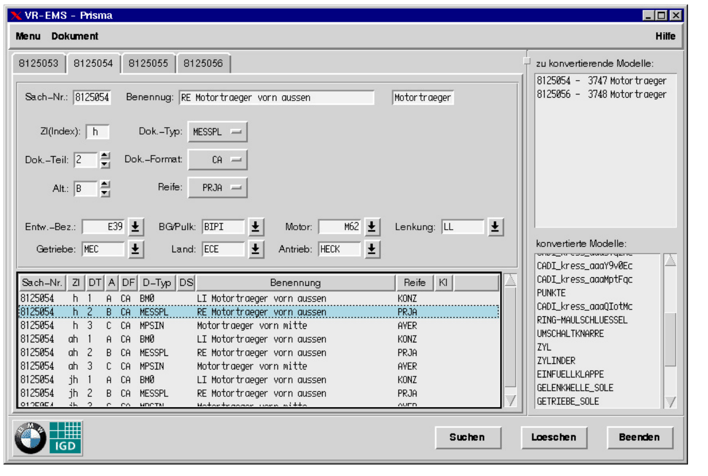

Figure 3. A preparation tool for retrieval/conversion of CAD data for visualization and simulation in VR. (Developed by IGD and BMW)

even significant ones) can be made during the build-time. Therefore, by the time results are obtained by the PMU verification they have no more a direct correlation to the current design. Even if there have not been changes in the design, the "transfer" of the results of the PMU verification to the DMU is, in some cases, very difficult.

Vision Most companies already define their products digitally (e.g., CA methods) and manage the data by product data management systems (PDM). However, the digital data are not used as the basis for the core business process. Instead, they are maintained in parallel to a more traditional process based on physical mock-ups, more as an auxiliary or "support" of the PMU process or the building of PMUs.

The goal of DMU is to replace the traditional business process, based on PMUs, by one which fully maximizes DMU technologies available today and in the future. The visionary goal is a process with only a single PMU for a final verification, certification, and release to volume manufacturing (Dai & Reindl, 1996).

The goal is to perform verifications as early as possible, i.e., *front-loading* of engineering, manufacturing, service, manufacturing, and recycling tasks to the concept phase. We believe that by utilizing VR, digital mock-ups can be evaluated in the concept phase.

Objectives of the verification of assembly processes Objectives can be classified by two categories: *strategic* and *operative*.

Strategic objectives are global and involve the complete business process. The most important ones are: reduction of development costs, development time, and time-to-market; increase of product innovation, product quality, flexibility, and maturity at series start.

Operative objectives are more local, related to only one or a few key-processes. The most important objectives which need to be fulfilled for assembly and maintenance are (Pahl & Beitz, 1996):

- service, inspection, and repair locations should be easily accessible;
- visibility should be ensured;
- exchange of components should be easy;
- use few and standard service and inspection tools;
- accessibility of service tools, and hand and arm of the worker;
- calculation and investigation of minimal distances to avoid collisions, e.g. during operating conditions;
- calculation of assembly/disassembly paths for off-line robot-programming;
- calculation of sweeping envelop of movable component for packaging investigations, e.g. for reservation of space in engine bay.

Additionally, these objectives must be verified with 1–20mm precision, related to the business process phase . They must be documented in digital form. These electronic reports should be managed by the PDM system together with the geometry and further administrative and technological data. As soon as a new version of a electronic report is created, the PDM system should

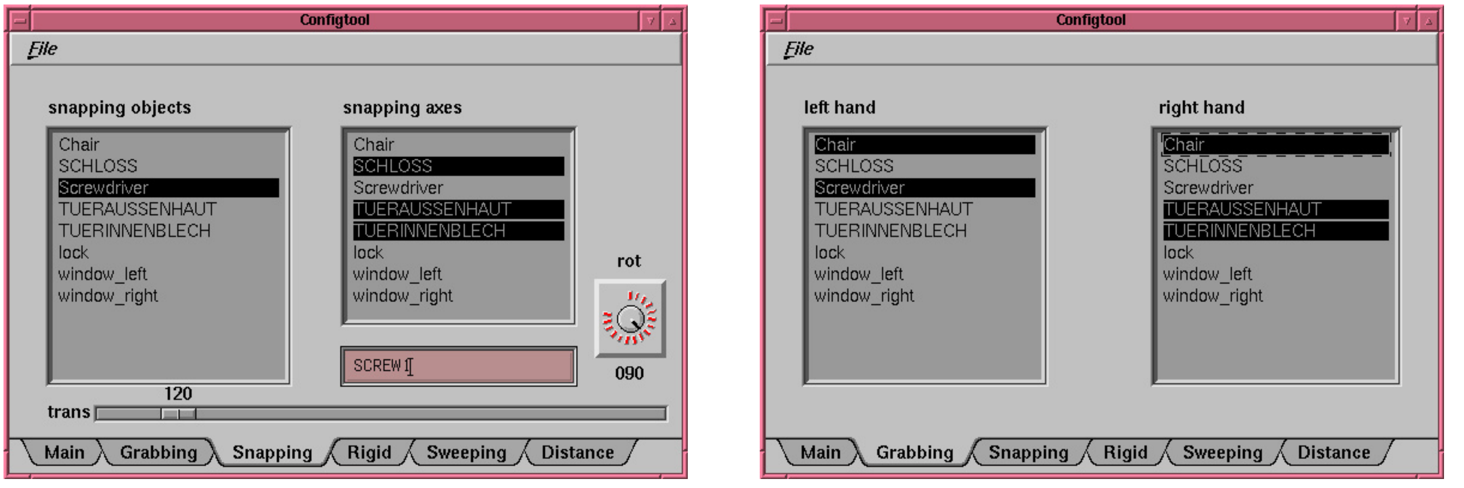

Figure 4. For every application domain there must be an application-specific authoring tool which provides the type of high-level functions needed in the particular domain.

inform involved users, that a new report is available for assembly processes.

The electronic report contains information related to simulation and investigation results, proposals for changes of CAD components, assembly/disassembly paths, collision areas, sweeping envelopes, and the status of all verification processes.

4 FROM CAD TO VR

The complete data pipeline from the CAD system to the VR system has various modules. CAD systems are the source of most of the data. This data is stored in a PDM system, which also maintains administrative data together with CAD data, such as ID, version, name, project code, etc. Via a retrieval and conversion tool these data can be converted, reduced, and prepared for use in a VR system (see Figure 3).

Common problems, especially with old data (i.e., CAD data designed for old products, but re-used in new ones), are the orientation of normals, missing geometry, and deletion of interior or other "unwanted" geometry. To our knowledge, there are no commercial tools available yet which can solve these problems automatically. So the process for preparing data for VR needs to access the CAD system interactively. We have tried to depict that in Figure 2 by the arrow between CAD and preparation tool.

CAD data requirements Design data available today in the manufacturing industries and others do not meet the geometric and non-geometric requirements so they can be used as-is for a VR simulation. There are two ways to tackle the problems described in the previous section: new data must be designed with virtual prototyping in mind; old data must be dealt with, either by redesigning (least preferred), or by semi-automatic conversion to representations suitable for VR.

It is commonly understood that design data has to have different representations depending on the phase in the business process (e.g., concept, engineering, etc.) and the key process that is to be verified (Spooner & Hardwick, 1997). For example, in the same CAD model there should be geometry and non-geometric information, like kinematic constrains, material properties, weight, etc., that will be used later-on during a VR session.

To avoid that designers have to become familiar with different software tools, the number of interfaces has to be kept low. To achieve an *integration* of the two worlds needs to take place. Ideally, a designer can be the one that creates the CAD components and also the one that performs assembly feasibility studies. Also, with a full integration it will be also easier to exchange data between CAD/PDM systems and VR systems.

5 IMMERSIVE VERIFICATION

In this section, we will briefly explain the process of authoring VEs, present the two scenarios which have been chosen for our studies and developments, and finally describe the functionality needed for assembly investigations.

5.1 Authoring

In order to make virtual prototyping an efficient tool to save time, it must be easy to "build" a VP, i.e., a virtual environment (VE) which represents part of a car and simulates part of its physical behavior. It must be at least as easy as designing with a CAD system.

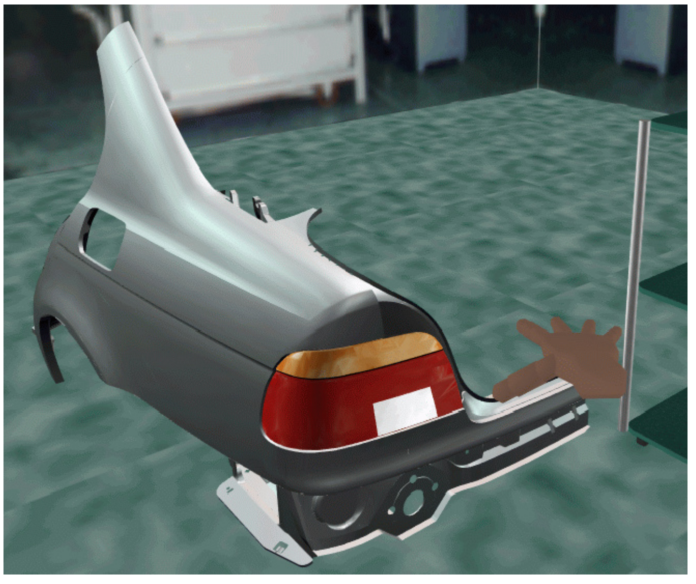

Figure 5. Overview of the tail-light scenario. The tail-light is to be removed.

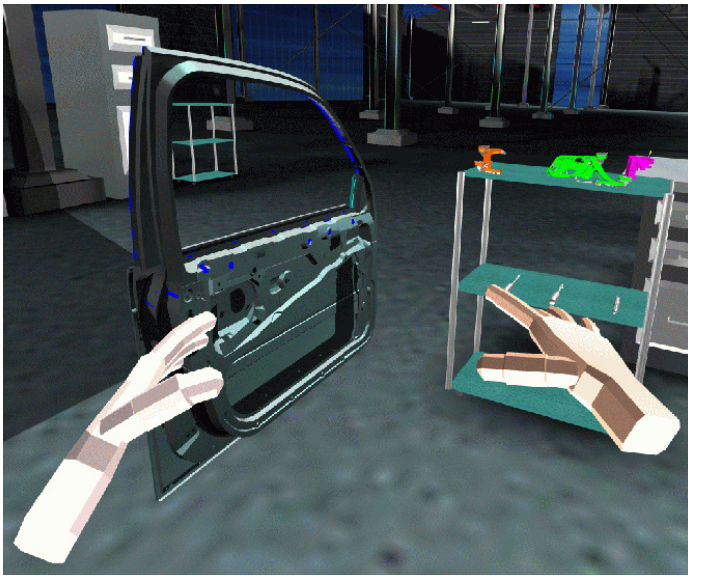

Figure 6. The door scenario. Two hands and several tools are necessary to perform the assembly.

We have developed a three-layer framework; each layer provides a certain level of abstraction and specialization. It has proven to be flexible and powerful.

The bottom layer is the *scene graph*: it deals mostly with geometry and rendering optimizations. Some scene graph APIs, such as VRML2.0 or Inventor, also provide very low-level scripting features.

At the next level we have implemented the *event-based scripting* approach for building VEs (Zachmann, 1996). It is a general framework based on the concept of *objects*, *actions*, and *events*, each of which with higher-level, yet general "story-board driven" functionality.

End-users working in a certain application domain (such as assembly simulation) will specify scenarios at the *application layer*, which provides a graphical user-interface (see Figure 4) and specialized, very high-level functionalty (e.g., the user tells the system which objects are tools).

Scenario templates If parts had standard names, then a large portion of VEs could be derived from standard "scenario templates", e.g., "front door", "tail light", "gear box", etc. So, for a VR session with a different geometry, a VE author would only have to modify one of those templates.

However, it is not clear to us yet, whether designers will ever design all the VR-relevant attributes. Some of them are geometric, like visible material, thickness of metal sheets, and the like. So far, a lot of authoring time is spent basically on specifying the non-geometric (semantic) attributes of parts, such as the function of objects (screw, tool, etc.), non-geometric materials (flexibility, smoothness), the order of tasks in the (dis-)assembly process, etc.

5.2 Scenarios

We have chosen two scenarios in order to assess a first set of functionalities needed for assembly tasks in VR; one of them is a simple one, the other is one of the most difficult. One of the scenarios (the door) was also used for the user survey.

5.2.1 The tail-light The first scenario is the disassembly of the tail-light of the BMW 5 series (Figure 5). First, the covering in the car trunk must be turned down, in order to get access to the fastening of the lights (Figure 8). To reach the screws fixing the tail-light, the fastening needs to be pulled out.

Then the tail-light itself can be unscrewed by a standard tool. After all screws are taken out, the tail-light cap can be disassembled by pulling it out from the outside.

5.2.2 The door This scenario is much more complex and more difficult in that both hands and various tools must be utilized (Figure 6).

The first task is to put the lock in its place in the door. This is quite difficult in the real world, because it is very cramped inside the door and the lock cannot be seen very well during assembly. Screws have to be fastened while the lock is held in its place (Figure 10).

Next, the window-regulator is to be installed (Figure 11). This task needs both hands, because the window-regulator con-

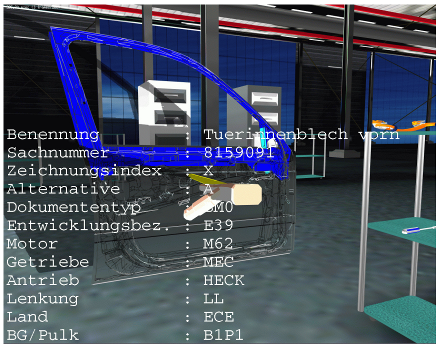

Figure 7. Administrative data stored in the PDM about parts can be displayed during the VR session.

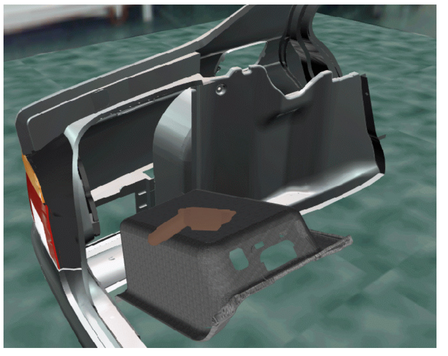

Figure 8. Inverse kinematics is needed for "door-like" behavior of parts.

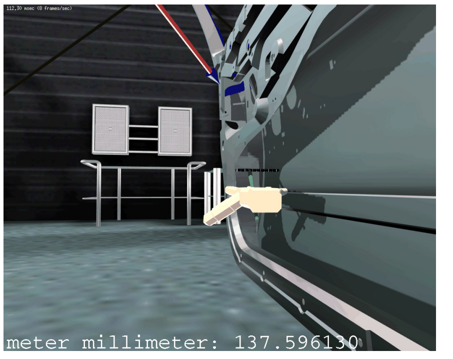

Figure 9. With the virtual yard-stick distances can be measured in the VE.

sists of two parts connected to each other by flexible wires. After placing the bottom fixtures into slots, they must be turned upright, then the regulator screws can be fixed.

Finally, several wires must be layed out on the inner metal sheet, clipped into place, and connected to various parts. However, this part of the assembly was not performed in VR.

5.3 Interaction Functionality

In this section, we will describe an array of techniques most of which have proven to be helpful in verification of assembly simulations.

Multi-modal interaction. It is important to create an efficient human-computer interface, because the tasks to be performed in virtual prototyping can be quite complex. Each technique must be implemented in a very robust and user-independent manner, otherwise users will become irritated and disapproving of VR.

Therefore, all "input channels" available should be utilized for the human-computer interface: both hands, gesture recognition, speaker-independent voice recognition, and combinations.

An on-line service manual. We believe that VR could eventually become an efficient means for training service personnel and an interactive service manual. Service manuals could be disseminated in the form of VRML environments, which can be viewed and interacted with on a PC based "fish-tank" VR system. In order to provide a combination of interactive, virtual training and a hands-on experience, augmented reality (AR) based systems might become necessary. Especially in larger and more complex vehicles, such as aircrafts and submarines, because it seems to be increasingly difficult to build mental maps of VEs presented on desktop systems and transfer those into the real environment.

In our environments we have implemented an interactive service manual as well as an interactive training session. First, a trainee *learns by watching* the service manual; this is basically an animation of the assembly process. While the animation is being played back, the trainee can move freely about the environment and watch from any viewpoint.

When the trainee is ready to *learn by doing*, he will perform the task step by step. After each step is completed the system will point him to the part or tool he will need for the next step and tell him what to do with it. For instance, after all screws for the door lock have been fastened, the system highlights the window regulator (by blinking) and instructs him how to assemble it. The instructions have been pre-recorded and are played back as sound files.

So far, the virtual service manual and the interactive training session are hand-crafted via manual scripting. However, it should be straight-forward to extract them from a PDM system, *if* the process data are there in a standardized form.

Getting help from the system. When the number of functions becomes large in the VR system, it can happen that occasional users can't remember some commands (in our current system there are about 40 functions). Similar to 2D applications, we additionally provide hierarchical 3D menus. In our experience, 3D menus are to be considered only as an auxiliary interaction technique, because it is more difficult to select menu entries in VR than it is in 2D.

Investigation tools. In order to make the correct decisions, it is important that the user can get information about the parts involved in the VP currently being investigated. Administrative information about parts can be displayed in a heads-up fashion by pointing at objects with a ray (see Figure 7). Of course, any other selection paradigm can be used as well.

A tool which has been requested by designers is the *clipping plane*. It can help to inspect "problem areas" more closely. When activated, the user "wears" a plane on his hand; all geometry in front of that plane will be clipped away. Optionally, the

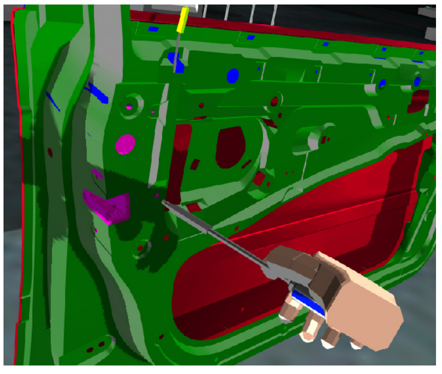

Figure 10. Tools snap onto screws and are constrained. Also, they are placed automatically at an ergonomic position within the hand by the system.

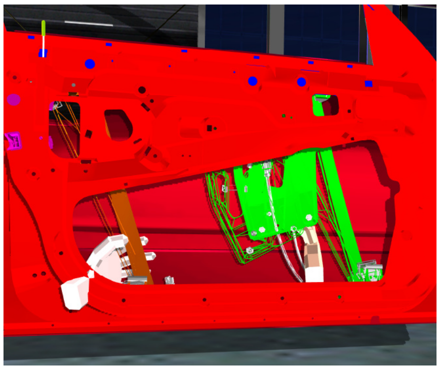

Figure 11. The window regulator has to be installed with two hands; the "ghost" paradigm signales collisions.

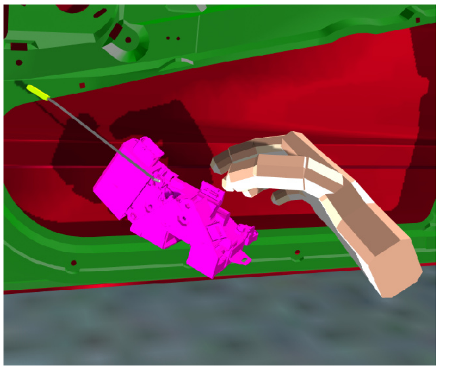

Figure 12. The *object-on-the-lead* paradigm allows to verify assembly. The object is not linked rigidly to the hand.

part clipped away can be rendered transparently. The plane can be released from the hand and grabbed again, so that the user can move freely while the clipping plane remains motionless. Sometimes it can be necessary to restrict the motion of the plane so that it is always perpendicular to one of the world coordinate axes. By utilizing an OpenGL feature clipping can be done at interactive frame rates with a geometry of about 60,000 polygons.

Another tool to inspect assembly situations and the mechanical design is the *user size*. This parameter can be controlled by simple speech commands, which in turn affect all parameters by which a virtual human is represented, in particular navigation speed and scale of position tracking. This way, a user can comfortably "stick his head" inside some narrow space.

In order to measure distances we have implemented two options: A user can select two objects, then the system will compute the *minimal distance* between the two and display it in the heads-up display. Or, the user can grab a *virtual yard stick* (see Figure 9). While grabbed, the yardstick adjust its length in both directions so that it just touches the closest geometry. Additionally, its length is shown on the heads-up display. Another way would be to select two points on the geometry and have the system draw a line between them and select the length of that line.

Physically-based simulation. Many mechanical components have some articulated parts. These could be simple "door-like" mechanisms (see Figure 8), i.e., permanent joints with one rotational degree of freedom (DOF), such as hoods, lids, etc.; other very simple ones are sliding mechanisms (one translational DOF), for example the seat of a car. Inverse kinematics of these and other articulated chains can be simulated on-line.

For complicated kinematic simulation, such as the working conditions of a complete chassis, we have pursued a different approach: the VR system loads the results of an off-line simulation by a commercial package, such as Adams™. The user can then interactively steer the visualization, for example by turning the steering wheel or by speech commands.

A lot of the parts in a vehicle are flexible: wires, hoses, plastic tanks, etc. It is still a major challenge to simulate all these different types of flexible parts with reasonable precision and at interactive rates. In particular, simulation of the interaction of flexible objects with the surrounding environment and the user's hands by a general framework is, to our knowledge, still unsolved.

We have implemented hoses and wires in our VR system; the wires or hoses are attached at both ends to other, non-flexible parts, and they can be pushed or pulled by a user's hand.

Verification without force-feedback. In our experience, assembly tasks are more difficult in VR than in the real in world, because in VR there is no force and haptic feedback (see also Section 6). Humans can even perform quite complicated tasks without seeing their hands or tools merely based on auditory, haptic and kinaesthetic feedback. Therefore, we have provided a lot of interaction aids trying to compensate for the missing force feedback.

In order to help the user placing parts, we have developed two kinds of *snapping* paradigms: the first one makes objects snap in place when they are released by the user and when they are sufficiently close to their final position. The second snapping paradigm makes tools snap onto screws when sufficiently close and while they are being utilized (see Figure 10). The second paradigm is implemented by a 1-DOF rotational constraint which can be triggered by events.

The major problems is: how can we verify that a part can be assembled by a human worker? A simple solution is to turn a part being grasped into what we call a *ghost* when it collides with other parts: the solid part itself stays at the last valid, i.e.,

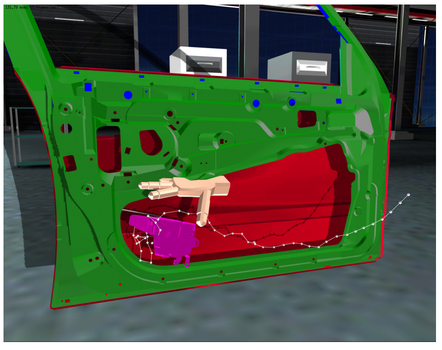

Figure 13. During assembly, the path of any part can be recorded, edited, and stored in the PDM system.

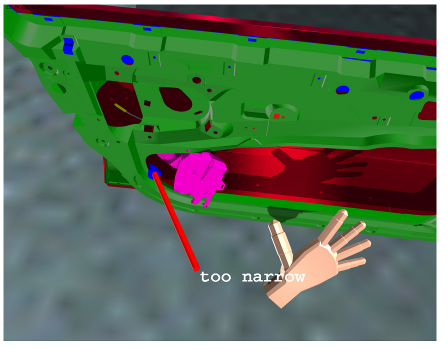

Figure 14. Annotations can be put into the scene by voice commands.

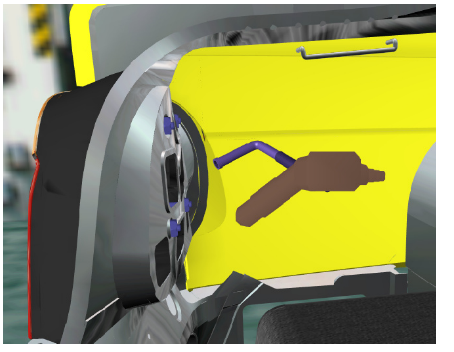

Figure 15. Violations of security-distance are highlighted by yellow, collisions are red.

collision-free, position while the object attached to the user's hand turns wireframe (see Figure 11).

However, invalid positions can be "tunneled". Therefore, we have developed the *object-on-the-lead* paradigm: the object is no longer attached rigidly to the virtual hand; instead, it "follows" the hand as far as it can go without penetrating any other parts (see Figure 12). We have implemented a physically-based simulation, so that the object can glide along other parts; in our earlier implementation, there was no gliding, which caused the object on-the-lead to get stuck in tight environments. So, at any time it can assume only valid positions. Of course, exact and fast collision detection is a prerequisite (Zachmann, 1998).

This is only a first step. A completely reliable verification will check the virtual hand for collisions as well. Also, the hand and/or part should slide along smooth rigid objects to make assembly easier for the user.

Feedback to the user. Any VR system should be as responsive as possible, especially for occasional, non-expert users. The users targeted for immersive VP will probably not use VR every day. Therefore, multi-sensory feedback is important to make them feel comfortable and in control.

Therefore, the system acknowledges all commands, in particular those invoked via voice recognition. Currently, this is done by pre-recorded audio or speech. Eventually, we will utilize speech synthesis.

During the assembly simulation, a variety of feedbacks can be combined which will be given if the user tries to move an object at an invalid position: acoustic feedback, tactile feedback by a Cybertouch™ glove, and visual feedback. Visual feedback comes in several flavors: whole parts can be highlighted (see Figure 15), or the polygons which would have intersected at the invalid position can be highlighted.

Documentation. If a certain assembly task cannot be done, then the result of the verification session should be a precise as well as intuitive understanding why that is. A number of techniques have been implemented in order to investigate and document a possible failure of assembly.

During assembly/disassembly the path of any part can be recorded and edited in VR (see Figure 13). Saved paths can then be stored in the PDM system.

While parts are being moved, the sweeping envelope can be traced out. It does not matter whether the part is moved interactively by the user or by playback of an assembly path.

Problems can be annotated by placing 3D markers (we have chosen 3D arrows). Then, verbal annotations can be recorded and displayed textually next to the marker (see Figure 14). Note that all interaction is done by the user via speech recognition, except for placing the marker. Eventually, the markers and annotations can be exported and stored with the parts in the PDM system.

6 USER SURVEY

In order to evaluate the acceptance and the potential of VR for VP, a survey of prospective users has been performed at BMW.

We have chosen a representative set of people from five groups involved with assembly and maintenance investigations. They were:

- *CA specialist (CA).* These are engineers that have a good CA expertise and also some specific assembly/maintenance processes knowledge.
- *Skilled worker (SW).* These are skilled mechanics who actually perform the physical prototype verifications. This group has no CA knowledge.
- *Interface specialist (IS).* This group comprises mechanical technicians. They have mostly specific assem-

bly/maintenance process knowledge, but they are starting to get familiar with CA tools. This group mediates between group 1 and group 2.

- *Managers (MA).* They are the ones that co-ordinate all the three groups in the vehicle prototype group.
- *IT specialists (IT).* In this group are very highly skilled engineers that do development and evaluation of new CA methods and IT tools. They provide new technologies to the key-user's departments (the above four groups are from the key-user department vehicle prototype).

Notice that all subjects have never before been exposed to any VR experiences.

The scenario used for the survey was the installation of the door lock, which is a very difficult task, because the space inside the door is very tight. Only subjects from group SW were to completely install the lock with their "virtual hand", because they are the only ones who really know how to do it. For all other groups, subjects were to focus on the "feel" of the technology, the I/O devices, and interaction techniques and capabilities.

Each group consisted of 5-7 persons, which gives a total of approximately 30 persons. Each group had 3 to 4 hours: one hour introduction, presentation of all the I/O devices and VR functionality of the VR assembly application, and for each person 20-30 minutes to perform the following tasks: navigate in the VE with a data glove; grasp and install the door-lock while recording the assembly path; invoke some functions (see Section 5.3) via voice input to analyze and manipulate components (PDM information, change color, clipping plane, etc.).

While one user was performing the verification tasks, all other users in the group were watching on a large-screen stereo projection with shutter glasses.

Hardware: SGI ONYX with 6 processors, 2 IR graphics pipes, 1 GB RAM, FS5 head-mounted display, CyberTouch$^{\text{TM}}$ data glove with tactile feedback, stereo projection, Ascension electromagnetic tracking system.

6.1 Evaluation

The results that are presented below were obtained with a questionnaire that each subject filled out after the VR experience. Each question was to be answered by a multiple choice with five levels: very good ($\hat{=}100\%$), good, satisfactory, bad, and very bad ($\hat{=}0\%$).

6.1.1 Navigation The possibility to move in 3D space without having to deal with 3D coordinates of points and vectors was an impressive experience for all groups. The natural and intuitive way to walk like in the "real world" is an important aspect for the acceptance of this technology (see Figure 16).

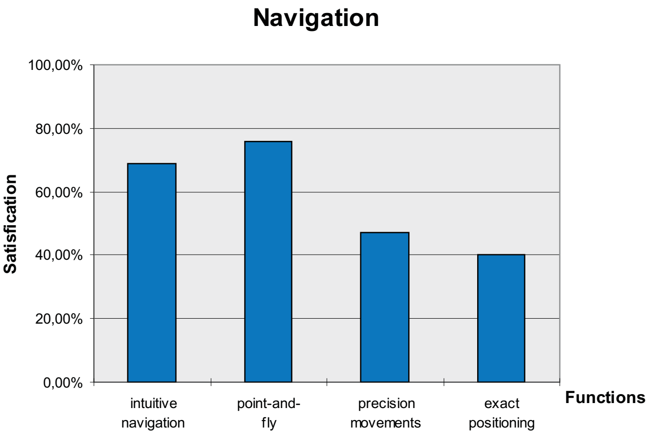

Figure 16. Navigation in the VE with a data glove.

During the investigation subjects could navigate by point-and-fly. However, most of them disliked it, because it was unconstrained. They said: "In the real environment we have only the possibility to walk. If the car is too low or too high, we can lift the car." When we informed them, that the system also provides point-and-fly constrained to eye-level, they rated this paradigm very high.

Most users were missing precision movements of the viewpoint and exact positioning of parts in the VR system. Of course, we expected this; yet, we chose not to burden the session by two many tasks, although parts can be positioned exactly with the VR system by voice commands. In this survey however, users were only shown the point-and-fly navigation and how to position parts by using the glove.

6.1.2 Voice input As Figure 17 indicates almost all subjects preferred voice input for giving commands to the computer. We believe that this is due to the very natural way in which commands can be given, e.g., a user just says "selection on" or "switch selection on". Some tasks can be performed much more precisely with a binary trigger than by a virtual hand, for instance exact positioning.

Unfortunately, interaction by voice recognition has two shortcomings:

- We need to utilize user-independent speech recognition because occasional users like mechanics will not accept to train the speech recognition system prior to a VR session. Therefore, the recognition rate is a little bit lower than with a user-dependent system. However, even a recognition rate of 90% irritates occasional users a lot.

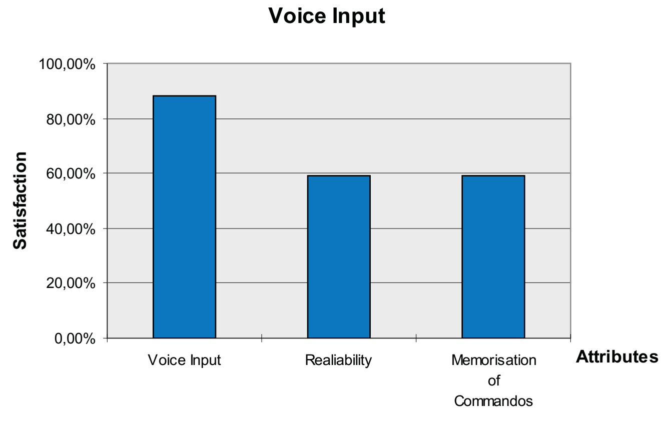

Figure 17. Although the reliability and easy-of-memorization got only a medium rating, user's preferred voice input significantly for giving commands to the VR system.

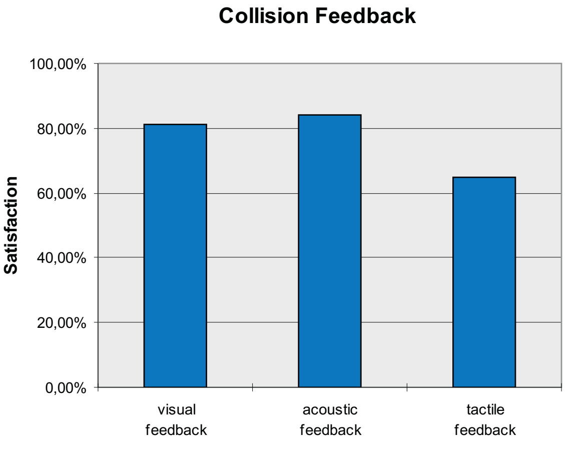

Figure 18. Evaluation of several collision feedbacks. Tactile feedbacks was given through the CyberTouch's vibrators.

- Occasional users won't remember too many commands, so they often have to use 3D help menus in order to recall them.

This is why the user satisfaction with voice recognition reliability and command memorization is significantly less than the overall satisfaction.

6.1.3 Collision feedback

An interesting result of our survey is the response regarding feedback. In particular, we asked the users to evaluate the multi-modal feedback given by the system in case of a collision: visual, acoustic, and tactile. We use the Cybertouch^{TM} to produce tactile feedback. Each finger's vibrator was controlled individually by the VR system.

The result of the survey can be found in Figure 18. We believe that the visual feedback was not completely satisfactory to the users, because it highlighted the whole object instead of the area of collision only, which is what engineers are interested in.

Acoustic feedback plays a main role in two different ways: first, it provides feedback to the use what is happening at the moment; secondly, it provides information about the material (e.g., metal, wood, plastic, etc.) of the colliding components consist of.

Tactile feedback was evaluated significantly less helpful than the other two. Although our subjects found it an exciting experience, it is nevertheless unnatural to them. After some discussion with them, we realized that what they really would have liked is *force feedback*. They reported that without force feedback some assembly tasks are almost impossible to do.

7 CONCLUSION

In this paper we have discussed the benefits of virtual reality for virtual prototyping in assembly and maintenance verification. Also, the integration of VR with a company's existing CA infrastructure has been discussed. Several problems have been adressed and solutions have been proposed.

We have presented several interaction paradigms and functionality which a VR system must implement in order to be suitable for that area of application. They enable unexperienced users to work with virtual prototypes in an immersive environment and help them experiment efficiently with CAD data. All features and frameworks have been implemented in Fraunhofer-IGD's VR system *Virtual Design II*, which has been successfully evaluated by BMW in a benchmark; it will be employed routinely by BMW for virtual prototyping in the future.

Finally, we have reported on some results of a user survey performed at BMW with a representative group of key users. The result of our survey indicates that the use of VR for VP will play an important role in the near future in automotive (and probably other) industries. In particular, the response of the surveyed users has been very encouraging and optimistic that VR/VP does have the potential to reduce the number of PMUs and improve overall product quality, especially in those processes of the business process chain where humans play an important role.

VR is the best tool (today) to obtain quick answers in an intuitive way in the concept phase of the business process of a product, because in that phase data change often and are available only in a "rough" preparation. However, we cannot provide a formal cost/benefit analysis at this time, since the technology is not yet integrated in the daily productive work environment of our business process.

However, VR will not become a wide-spread tool in manufacturing industries before it is seamlessly and completely integrated into the existing CA and IT infrastructure[2]. This is not only a question of conversion and preparation tools: a lot of the data needed for a complete digital mock-up are just not there yet, such as process information, material properties, etc. All automotive and aerospace companies have realized that and are working on implementing solutions. However, this does not only involve technical aspects of the design process but also a tremendous shift in corporate culture.

Future directions From our experience we feel that current VR I/O devices are still way too cumbersome, and not robust enough, to be used in CAD working environments or on workshops.

Especially in virtual assembly and maintenance simulations acoustic feedback turned out to be not sufficient to meet the demands of the users. A comfortable-to-use force feedback device would extend the immersion and usability, enabling the user to do assembly/disassembly tasks in narrow and complex virtual environments, particularly if the parts, tools, and/or hands cannot be seen during the task. Mechanics "see" with their hands; therefore, force feedback would add significantly to the degree of immersion, and it would give a natural and expected feedback how to solve collisions. Furthermore, it prevents a deviation of the (real) hand and the grasped part.

Another problem is the way engineers are designing today. It is still quite difficult to prepare CAD data such that an interactive frame rate will be achieved by the VR system both in rendering and in simulation speed. This problem might be solved in a few years by faster hardware. However, a lot of the semantical (non-geometric) data needed in a virtual environment just do not exist. This can be solved only in a shift in the design process: design guidelines have to be established with virtual prototyping in mind, and some data just have to be modeled for VP either by CAD engineers or by "VP engineers".

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[2]For instance, in order to create a complete VE for immersive assembly simulation we need 70% of the time to find and prepare the CAD data and only 30% for authoring the VE.

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