Augmented Reality Projects in the Automotive and Aerospace Industries

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[Analyzing 5 years of work and 10 of our Augmented Reality projects shows: Real applications are challenging.]

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Abstract
In 2003 the International Symposium on Mixed and Augmented Reality (ISMAR) was accompanied by a workshop on Potential Industrial Applications (PIA). The organizers wisely called it "potential" because the real use of augmented reality (AR) in an industrial context is still in its infancy. Our own experience in this field clearly supports this viewpoint.
We have been actively involved in the research, development and deployment of AR systems in the automotive, aviation and astronautics industries for more than five years and have developed and implemented AR systems in a wide variety of environments. In this paper we have selected ten AR projects from those we have managed and implemented in the past to examine the main challenges faced and to share some of the lessons learned.
We will conclude with some guidelines for successfully deploying AR in an industrial context.

Introduction: Augmented Reality in an industrial context
Bringing research results out of the laboratory and into an industrial context is always a challenge. And if this process eventually leads to success on the market it is usually called innovation.
Innovations in the technological area of augmented reality are rare. On the one hand research and development (R&D) is still in its early days. On the other hand the academic and industry partners both agree that there is huge potential for the technology in a broad variety of applications. As a result various attempts to bring R&D and “real world use” of AR together have been made and are still top of the list for potential innovations.
It can be said that the application of augmented reality in an industrial context started with Boeing’s wire bundle assembly project in the early 90’s (Mizell, 2001) followed by several smaller projects until the end of the last century. While numerous academic projects evolved in the following years, industrial augmented reality (IAR)

applications are still rare. In some cases, AR technology was applied successfully in certain use cases. For instance in supporting welding processes (Echtler et al., 2003) or in some training scenarios (see Doerner et al., 2002).
To date there have been two major initiatives for AR innovation. The Mixed Reality Systems Laboratory in Japan, with its focus set on the development of mixed reality prototype applications comprising hardware and software, has demonstrated the potential for the real-world use of AR (see Tamura, Yamamoto, & Katayama, 2001). The successes of this project lead to the release of the mixed reality platform, a comprehensive toolkit consisting of display, tracking, and AR software technology. The other initiative being the German project "ARVIKA" lead by Siemens which included the majority of the manufacturing industry in the country as well as selected partners in academia and small and medium enterprises (see Friedrich, 2004). The focus here was on the application of AR in the fields of design, production, and servicing.
All these initiatives brought forward various prototypes and demonstrated applications and have therefore been valuable in progressing the field of AR. The lessons learned in these projects have had a strong influence on the direction of AR R&D worldwide.
As part of this international community we have developed prototypes of AR applications in the realm of automotive and aerospace industry. A majority of our projects are presented here.

Servicing and Maintenance

Today's products are getting more and more complex. The days when a plan of the electrical circuits of a car fit onto one large sheet of paper have long gone, modern high-tech cars now require a database system and state of the art computer equipment for electric and electronic diagnosis. A printout of such a database is as thick as an encyclopedia.
How can one bring the right information to the right place at the right time? The use of augmented reality technology seems to be obvious. The service personnel is equipped with a (wearable) computer unit and gets the appropriate information displayed next to or overlaid onto the object being inspected. Not only can this do away with the need for a paper schematic, but a far richer information resource can be provided via online access to dedicated information and multi-media content. The promise is to increase effectiveness (fewer errors) and efficiency (shorter time to complete the task) through the use of context-sensitive, up-to-date, and media-rich information.
All major manufacturing enterprises are thinking about how to make use of AR technology in their maintenance and servicing areas. The more complex the product is, the greater the potential benefit of AR.
We have selected three areas where we applied AR technology for service personnel.

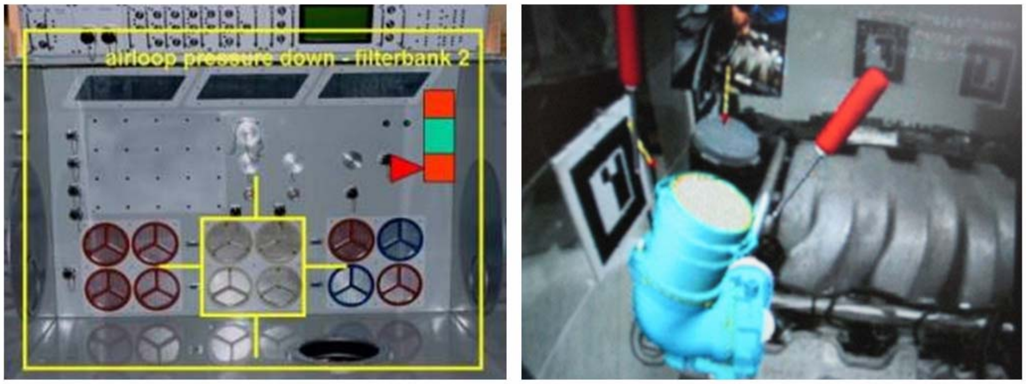

Figure 1: Servicing projects from left to right: Space station filter change and engine maintenance

Space station filter change

The European Columbus module of the International Space Station (ISS) is intended to be inhabited (part-time) by astronauts from different countries. As one can imagine this module is a very complex system and requires many maintenance tasks to be undertaken by the astronauts. The augmentation of service information could help decrease the workload. The client for this application (German and European Aerospace industry: DASA RI, EADS Astrium) decided on a step-by-step approach for testing the use of AR technology in space. A fairly simple application scenario was chosen to test the validity of the concept: providing instructions and support for monitoring the state of the air filter and changing the filter if required.

Our research and development involved the implementation of an optical see-through solution, the connection of this to a content delivery system, and the identification of opportunities and limitations of AR use in this context. The content delivery was entirely based on an existing virtual reality system. All information displayed was in the form of three-dimensional geometry modeled as a whole or in part beforehand. Together with developers in the client group, a whole wearable AR system was developed consisting of a rugged backpack computer, a modified COTS head-mounted display with optical see-through capabilities (Sony Glasstron), and an ultrasonic/inertial tracking system. Although it was intended to display three-dimensional content, in the end 2D content aligned to 3D space was provided (see figure 1 above).

The system was successfully demonstrated at an international aerospace fair, but the system never made it into space. This was due to the difficulty in meeting the rigorous requirements of aerospace standards, which include being able to withstand extreme operating conditions (e.g. high g-forces), the required unobtrusiveness of the technology within the module (almost no instrumentation of the environment is possible), or the failure-free linkage to the onboard information infrastructure.

Engine Maintenance

For the diagnosis of maintenance and repair tasks, modern cars provide a system interface (mostly via a plug-like connector). While this interface allows for very fast and precise analysis of the state of the engine, the accompanying information is still found on a dedicated PC or on print-outs. Hence, the object to which the diagnosis is applied (part of the engine) and the resulting data yielded by the diagnosis are spatially separated. AR has the potential to close this gap, enabling the diagnosis results to be displayed right in immediate proximity to the engine.

There are many important questions that must be considered, however: What kind of information is useful, and should it be represented? What are the technological alternatives available for solving this? If the data is very complex, as it often is, where and how do you place the information at the engine?
These were the issues we had to address when implementing a prototype application for a real Mercedes-Benz (8 cyl. SL) engine. Again, an HMD-based solution connected to a portable PC (alternatively, a notebook computer) was chosen. The tracking of the user's position and orientation was done using a marker-based approach. In this case markers were attached to a U-shaped object which was placed into a certain location at the engine. The use of multiple markers at well-defined positions provided us with reasonably precise tracking.
The following data types were presented (see figure 1 center): (1) maintenance and repair instructions taken from the garage information system, represented as textual and pictorial information in space, (2) pre-recorded video instructions in the form of a "virtual TV set" placed at a fixed position in space, (3) 3D models with predetermined animated sequences as overlays, and (4) a video/audio link to an expert technician as an example of remote technical assistance displayed with the TV set approach, too.
While the choice of computer and display technology is straightforward, taking into account such matters as cost, quality of design and reliability, the information provision is a bigger challenge due to various key factors: (a) The appropriate information has to be selected automatically out of the existing information system (normally text and graphics with references to 3D models), (b) the user interaction has to be supported in an easy-to-use way, (c) new multi-media content (esp. video and 3D models) has to be created and edited, and finally (d) the multi-media information has to be brought into a spatial relationship with the object (engine). This entire authoring process is currently subject to research and development (see Haringer & Regenbrecht, 2002) and clearly deserves stronger attention.

Tram diagnosis

Trams (street cars) as well as other forms of public transportation are very big objects with very widely distributed technological components, such as wire connectors, relays, fuses and electronic units. The interplay of these components is very complex and the maintenance of the entire system needs skilled technicians and highly developed diagnosis systems. In addition to the car maintenance example mentioned above, there are two main challenges: (1) An AR system needs to be wearable because of the distance between the components and (2) an information system linkage to the existing diagnosis systems is mandatory, because maintenance here cannot be done without such a system.
A back-worn wearable AR system incorporating a modified notebook computer and all peripheral components for a self-containing video see-through system was developed and tested in a laboratory setup simulating the real tram environment. A handheld computer with a touch screen display served as the main interaction interface to the diagnosis system. Both system parts (AR and handheld) are connected via wireless network technology to a dedicated server. The software running on the server links the systems together. The augmented view shows arrows pointing at the current diagnosis object, as well as explanatory texts.
While the system as a whole works very well in our laboratory setup, a real-world application is very unlikely in the near future. The main shortcomings of the approach are: (a) The instrumentation of the environment for tracking purposes is unacceptable. Neither fiducials nor other mounted sensors are practical. (b) The wearable unit

(approx. 6 kg) is too heavy to use for extended periods. (c) The wireless networking technology is not robust enough for a real-world environment (incomplete coverage). The network access point cannot be brought into the tram for every diagnosis due to practical workflow reasons.

Design and Development

Applying AR technology to a product itself (e.g. servicing) or the support of manufacturing processes (e.g. assembly instructions) is an obvious option. One often-overlooked opportunity however, is supporting the process of product design and development. Improvements in efficiency, in particular cutting development time, have a huge effect on the product itself and on the time-to-market. There is a clear competitive advantage if a product can be delivered earlier and with higher quality. In selected development process areas AR can make a significant contribution in achieving these goals. While the identification of possible applications for AR in the design and development area is more difficult compared to production or servicing, the chances for success are reasonably high due to system-friendly environments and the possibility of establishing the technology first with selected applications.

Airplane cabin design

Each airplane interior is designed according to the customer's (airline's) needs. In the process of cabin design and development, customers are usually an integral part of the design team. They are actively involved in design decisions influencing alternatives assessed and the selections made for the final product design. The design process involves many simulations utilizing both physical and digital mock-ups. While the geometric properties (e.g. seat placement, shape of lining, appearance of kitchens) can be simulated quite well, the simulation of some physical properties like temperature, speed and direction of air flow in the cabin, or air pressure, is more complicated. The implementation of a physical mock-up simulating these properties is very complex and not cost-effective.

The visualization of Computational Fluid Dynamics (CFD) data in the form of voxels (volume pixels) is a very common way to overcome this shortcoming. For instance, a high-pressure value at a certain location in the cabin is visualized as a very small yellow cube, a point of low pressure is visualized in red. The entire visualization of e.g. 128^3 voxels, looks like a colored cloud and can be used for the interpretation of cabin comfort. This interpretation is very hard if the spatial reference to the real environment is missing (e.g. displayed on a monitor). Augmented reality allows here for the combination of the real space, the cabin, with the CFD data sets.

We have integrated a self-contained AR system powered entirely from batteries into a flight attendant's trolley. The user's position and orientation is tracked with temporarily placed (PostIt-like) markers in the environment. Figure 2 shows the user's view of the environment with different levels of augmentation. It illustrates the usefulness of this approach: the final overlay of CFD data clearly maps to the environment being assessed.

Because we were using a virtual reality system as a basis for the AR system, the solution can be used for digital mock-up displays as well. Even elements of the cabin that have not yet been built in can be visualized in 3D with this system. Interestingly enough this is now what this system is primarily used for at the customer's site.

This prototype system is ready to use, but more design and engineering is needed to prepare it for long-term use. The HMD needs to be more robust and ergonomically designed, the update rate and robustness of the tracking system has to be improved, and the access to CFD and 3D model data has to be improved.

Figure 2: Overlay of CFD data, clockwise: cabin, CFD only, CFD and phantom model, final augmentation

Collaborative design review

The design and development process of a complex product involves many iterative engineering steps. Simultaneously developed parts have to geometrically and functionally fit together and have to be prepared for production and servicing processes, among other things. The main engineering task is to take into account all requirements and to find the best solution. This is a collaborative task by nature, because the decision-making process is far too complex to be done by a single person. Frequent meetings with specialists are the most common method of making design decisions. These meetings incorporate digital data (e.g. CAD models) as well as physical mock-ups and rapid prototype models. The construction of models of the physical components is both time consuming and expensive. Augmented reality offers the opportunity to integrate 3D data into the meeting environment without the need for constructing an actual physical model of the item. The result however, is almost the same as having a physical model with the object to be discussed appearing to "stand" on the table.

Our prototype system enabled four people wearing HMDs to have such a meeting (see figure 3). The object is virtually placed on top of a turntable - a rotating board ("cake platter" or "Lazy Susan") which serves as a tangible interaction device. For a more detailed description of the system see (Regenbrecht, Wagner, & Baratoff, 2002).

Besides the need for further development of the system towards a more efficient usability the main R&D tasks are (1) a tighter, more integrated link with the existing product data management systems and (2) the development of a way to visualize very large and complex data sets.

Figure 3: Meeting incorporating a virtual engine part

Cockpit layout

The huge number of displays and controls in an airplane cockpit needs to be designed very carefully considering many issues including functionality, ergonomics and safety, to name but a few. It is helpful in the early design phases to be able to discuss a rough layout of the cockpit in a collaborative setting and this can be achieved using AR technology. In this instance we provided a metal whiteboard with magnetic markers to which the cockpit elements were attached as virtual representations. This allowed for the designers to experiment with different arrangements and to annotate each of them. Figure 4 shows an inside view of the system, which is described in detail in Poupyrev et al. (2002).

When lighting conditions are set carefully, the system is reasonably robust and easy to use due to the tangibility of the interface. The combination of HMD and monitor display options makes the interface very flexible. The main restrictions lie in the limitations of available space for the elements on the whiteboard, the 2D arrangement of elements on the whiteboard and the lack of access to dynamic data. Therefore our solution is suitable only for very early design discussions and could be extended to other tasks or phases only with significant further research and development.

Figure 4: Early phase of cockpit layout

Production support

Whoever comes into a large manufacturing or production shop floor will immediately realize the difficulty in introducing any kind of sensitive equipment to such an environment. By their very nature these environments are crowded with workers and/or robots, are noisy, mostly tidy but dirty, have very little wasted space (no room for extras), and are a scene of endless activity that appears to border on organized chaos.

Given the requirement to provide a value-adding augmented reality application, the identification of a suitable workplace is very hard. AR technology at this stage of maturity is far from being robust enough to be applied to the whole manufacturing process. Together with internal and external specialists (ar-solutions.de, shared-reality.com) we have identified some application scenarios where AR could be applied successfully and could gain a reasonable return on investment. Below are three such potential applications of increasing technological complexity that illustrate the different stages of maturity.

Fuse placement

In the truck-manufacturing example considered here, almost no two trucks are really identical. The variety of options available to customers is wide-ranging. Because of the many possible combinations of these options, virtually every truck that leaves the plant is unique. This can be observed, for instance, with the placement of fuses and relays for the cockpit of the truck. According to a black and white schematic printed on paper (figure 5 left), a worker inserts fuses manually into a board. The various types of fuses are represented by numbers on the schematic (e.g. 15 means a red colored fuse). Figure 5 (center) shows the working environment. The board is brought into a fixed position on the table (and is connected to a control unit which sets the internal parameters of the board's electronics not considered here) where the operator manually installs the fuses.

Because of the fixed position of the board, an AR solution without any tracking is possible. In this example we placed a camera above the board and displayed the overlay on a computer screen which was already present in the environment. The overlaid image is shown in figure 5 (right).

This is an example of how a simple solution could be found because of the AR-friendly nature of the environment. It leads to a very robust, value-adding solution. This prototype is about to be introduced into the production process.

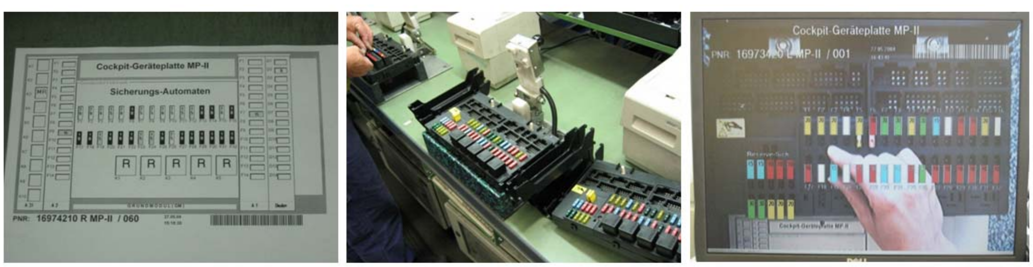

Figure 5: Fuse plan (left), working place (center), augmented view (right)

Picking

The process of picking can be described as manually seeking for a particular item in storage according to a list, (see figure 6 left) taking that object and putting it into the appropriate transport vehicle and bringing the objects to the required location for processing. Picking occurs in many manufacturing and dispatch businesses. In our case, car and truck manufacturing, picking is a necessary part of just-in-time assembly line production and is an entirely manual task. We have identified two main categories of possible improvement through the use of AR or similar technologies: (1) error reduction i.e. reducing the number of errors in reading from the list and reading the labels of the items in storage and (2) savings in the time taken to travel between different storage locations and to and from the transport cart with the list attached to it. After assessing the merits of several AR approaches we eventually decided on the implementation of an untracked, optical see-through head-worn display. The list information was brought to the worker in a more robust and failure-minimizing way (see figure 6 right for a list example).

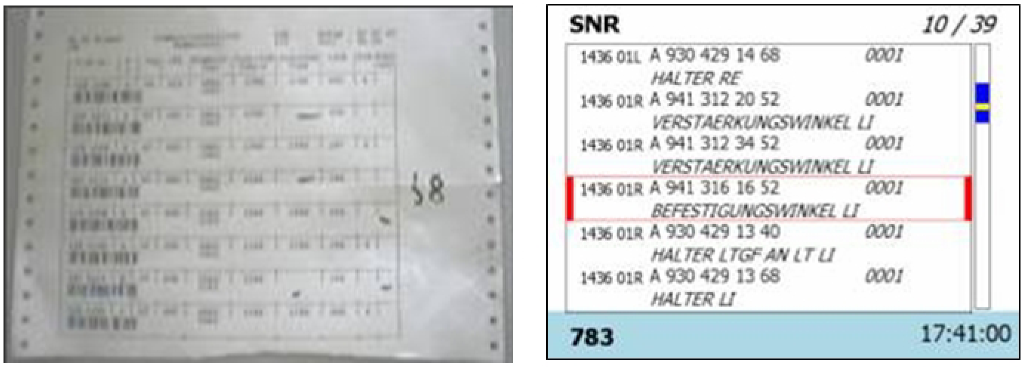

Figure 6: Picking list: left on paper, right in viewing device

To allow for comparison and usability testing we implemented two versions of the system: (1) a Microvision Nomad Expert Technician System and (2) a MicroOptical viewer connected to a Personal Digital Assistant. Both systems can be applied to the environment and offer different advantages. While system option #1 allows for an almost unobstructed view of the environment with a bright information display, system #2 is more lightweight and is capable of displaying in color (compared to monochrome red). The main disadvantages of both systems are the psychological barrier of introducing a device with a laser beam going directly into the eye (system #1) and partially blocking the view of sight (system #2). Figure 7 shows both systems with display examples inset.

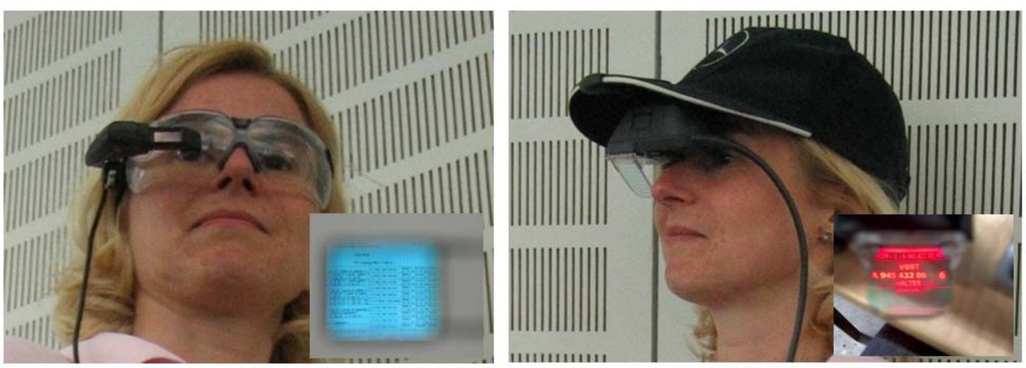

Figure 7: MicroOptical display (left), Nomad display (right)

The main challenges with both system approaches are: (a) the failure-free and instant provision of the data to be displayed, (b) the form of interaction (changing list items, changing lists, confirmation and abortion of actions), and (3) the seamless introduction and integration into existing work processes.

Wiring

As previously mentioned, some complex products offer so many build-to-order options that the number of possible combinations of these options is almost infinite. In our application for the truck assembly line, this was also true for the wiring inside the vehicle. Bundles composed of wires have to be configured and cut according to the aggregates and components to be controlled or powered. Because of the pace of the

assembly line this cannot be done in one single step. The paths for the wire bundles have to be measured at the start of the line. Then in a parallel, semi-automated process, the wire bundles are put together and finally installed at a later stage on the assembly line. The manual measuring step can be substituted by an augmented reality approach where virtual wire bundles are laid into the real geometry (in this case the girder of the truck) with on-the-fly data transmission to where the wiring bundles are constructed.
We decided to introduce and compare different hardware technologies involving combined active and passive optical tracking, HMD, large monitor, projection technology in combination with a software solution developed especially for this process. Figure 8 (left) shows a section of a truck chassis with wire bundles and figure 8 (right) the overlay of a wire bundle (in yellow) with mounting points.
While the software was well received by the users, the main shortcomings are: (1) the tracking systems used require too much instrumentation of the environment and are much too sensitive for the harsh environment (lighting conditions, vibrations, possible collisions with objects or persons). (2) The display technology used is neither robust enough nor ergonomically designed for extended use. A rugged (large) monitor solution does not give the impression of working “inside” the girder. The HMD solution is too obtrusive and a projection approach is impossible due to the black girder surface or too difficult to integrate into the working environment (e.g. Laser).

Figure 8: Girder without (left) and with (right) augmented wire bundles

Although Mizell (2001) applied AR in a slightly different context (wiring on boards distant from the actual production line) he came to similar conclusions. Eventually the introduction process was too complex and the available technology too immature to be entirely successful.

Training

One main advantage of using AR technology for training compared with virtual reality or other multi-media technologies is the possibility of on-site experiences for the trainee. Instead of teaching in a more or less abstract environment, the didactic information can be brought to where the final application will occur. We assume that one can imagine many possible training scenarios in different fields.
We have decided to present a more “exotic” scenario here to illustrate the possible scope of AR applications.

Driver safety training

Driving a car is a complex task requiring car-handling skills, knowledge of road rules, and driving experience. While the vast majority of drivers master standard traffic situations very well, unexpected events and adverse environmental conditions are always very challenging and sometimes create dangerous situations for the driver. This is as true today as it ever was even though today's cars are equipped with innovative assistance systems. ABS, ESP, ABC for instance, are abbreviations for safety systems found in modern car specifications. Even if the driver is familiar with the underlying principles of these systems, he or she may not always know how these systems work in extreme situations. Many automotive clubs, car manufacturers, and public and private agencies therefore offer driver safety programs. In a carefully controlled environment, the trainee learns to cope with adverse road and weather conditions and simulated accident situations rarely found in everyday life. Unfortunately the possibilities are limited nevertheless. For instance, a situation simulating a child suddenly jumping onto the street can be done only with very abstract substitutes (e.g. throwing an object onto the street manually). Augmented reality technology however, offers an almost limitless array of possibilities for experiencing extreme situations.

We developed a system that the driver and trainer can use within the car while it is being driven. Both, the trainee and the trainer wear head-mounted displays with video see-through capabilities (see figure 9 left). The virtually overlaid content is delivered by notebook computers located on the back seat (see figure 9 right). The current tracking uses a combination of fiducial and inertial systems. A number of driving scenarios have been developed together with the customer (the safety program agency) and implemented using standard virtual reality and animation tools.

From our customer's perspective this application is clearly seen as a value-adding addition to the existing programs. The trainees react in a very similar way compared to real scenes illustrating the effectiveness of the augmented content. The system is going to be re-engineered for quality improvements and multiple deployments.

Figure 9: Driver and trainer wearing HMD's (left) and augmented scene (right)

Lessons Learned

We have briefly introduced ten of our augmented reality projects applied in the automotive and aerospace industries. As shown above there are many technical and organizational issues to be resolved before one can apply AR in the field. Besides the application-specific issues addressed, some general guidelines can already be drawn from the experience we have gained. Even those may not represent empirical evidence; we think some humble suggestions can be made here that have value for anyone who wants to apply AR in an industrial context.

Data integration

Firstly, the effort required to incorporate real-world data into the AR application are often seriously underestimated. Most demonstration scenarios work pretty well with (manually) pre-configured and specially prepared data sets. When it comes to the first

real data trial, however, the systems mostly tend to fail. This is usually either because of the quantity of data needed, or the complexity and historic diversity of the data. One could probably argue that the data delivery and preparation falls outside the realm of AR research, but nobody else better understands the data interface than the team of end-users and AR researchers involved in the project. The early consideration of real-world data sets is crucial for the successful final deployment of the system.
If the existing data cannot be used right away, a dedicated workflow and tools (especially authoring tools) need to be developed for successful process integration.

Acceptance

AR technology and research has not yet reached a level of maturity that allows for a widespread deployment "from scratch". The initial application fields need to be identified very carefully with key persons in innovator roles. These persons should work together with the researcher as close as possible, should know the application field very well, and should be widely accepted among their colleagues to serve as a point of multiplication for later dissemination. If one cannot find such a person who fully accepts the approach and is willing and able to drive it to success, the entire project will probably fail. Furthermore, the integration of many parties in the early process of the project (managers, company physician, union representatives etc.) is laborious but worthwhile. Additionally, usability studies with representative subjects should be a part of every application project.
Finally, if one has the opportunity to choose between different application scenarios, the preference should be given to single-user, single-location, and single-task settings. There is a far greater chance of success if your AR system is setup in an "island" environment compared with, for example, trying to equip hundreds of workers with wearable AR systems.

Simplicity

Albert Einstein once said: "Keep it simple, but not simpler!" This is very true for industrial AR projects. From the researcher's point of view the best solution found might not be the one with the highest level of originality or novelty, but imagine if the users realize later on that there was a simpler, more elegant solution for their problem. The disappointment will probably put an end to future cooperation. It is advisable therefore to provide a simple, but accepted solution first and to build on it for advanced versions at a later time.
The maturity of AR display and tracking technology in particular, seldom allows for the use of the most advanced and most recent systems available. One has to consider all alternatives available. Choosing the most accepted and robust one is always better than offering the latest "bleeding-edge" technology.

Added Value

At the beginning of a planned project, consideration of factors like cost, quality, time and knowledge gain, helps and often enables the project to get started. Even if the figures are "educated guesses", estimates of the value added and sometimes even a return on investment appraisal are widely expected. Indeed, this is not the core competence of an AR researcher, but it is to be expected that the researcher will be concerned with these issues. Preferably one can find experts in the field of industrial economics to provide appropriate data or estimates.

In a mid-term perspective, augmented reality is on its way to become a productive tool in industry. The spectrum of application fields is very wide and early applications of the technology have already demonstrated its value. A comprehensive, multidisciplinary approach to future research and development conducted in partnership with potential users will bring about the increased use of AR.

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Footnote:

* This work was done while the authors were at DaimlerChrysler AG, Ulm, Germany