Augmented Reality Projects in the Automotive and Aerospace Industries

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Ten augmented reality projects from different industries help demonstrate the challenges and lessons learned in developing real-world applications.

The 2003 International Symposium on Mixed and Augmented Reality was accompanied by a workshop on potential industrial applications. 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 while working at DaimlerChrysler in Germany. In this article we have selected 10 AR projects from those we have managed and implemented in the past to examine the main challenges we faced and to share some of the lessons we learned.

AR 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's usually called *innovation*.

Innovations in the technological area of AR are rare. On the one hand, research and development is still in its early days. On the other hand, the academic and industry partners agree that there is huge potential for the technology in a broad variety of applications. As a result, various attempts to bring research and development and real-world use of AR together have been made and are still at the top of the list for potential innovations.

The application of AR in an industrial context started with Boeing's wire bundle assembly project in the early 1990s followed by several smaller projects until the end of the last century.[1] While numerous academic projects evolved in the following years, industrial AR applications are still rare. Some cases successfully applied AR technology in certain use cases such as supporting welding processes[2] or some training scenarios.[3]

To date there have been two major initiatives for AR innovation. The Mixed Reality Systems Laboratory in Japan—with its focus on the development of mixed reality prototype applications comprising hardware and software—has demonstrated the potential for the real-world use of AR.[4] 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, the German project Augmented Reality für Entwicklung, Produktion und Service [Augmented Reality for Design, Production, and Servicing], or Arvika, lead by Siemens, included the majority of the manufacturing industry in that country and selected partners in academia and small and medium enterprises.[5] This project focused on the application of AR in the fields of design, production, and servicing.

The various prototypes and applications that these initiatives brought forward have been valuable in the AR field's progression.[6,7] The lessons learned in these projects have had a strong influence on the direction of AR research and development 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 increasingly complex. The days when a plan of a car's electrical circuits 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.

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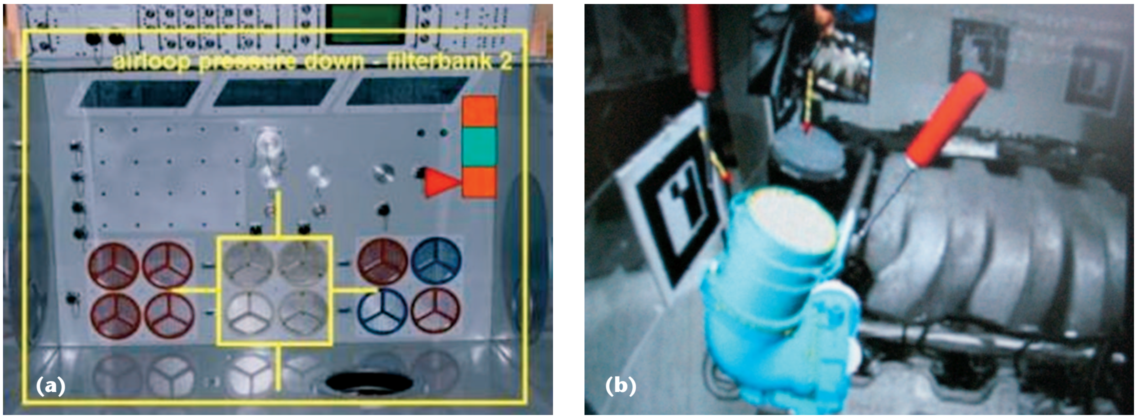


1 **Servicing projects: (a) space station filter change and (b) engine maintenance.**

The use of AR technology is an obvious way to help bring the right information to the right place at the right time. Service personnel equipped with a wearable computer unit can get the appropriate information displayed next to or overlaid onto the object they are inspecting. 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 multimedia 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 use 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: space station filter change, engine maintenance, and tram diagnosis.

Space station filter change

The European Columbus module of the International Space Station is inhabited (part time) by astronauts from different countries. The module's complex system requires the astronauts to undertake many maintenance tasks. The augmentation of service information could help decrease their workload. The client for this application—the German and European aerospace industry: EADS Astrium—decided on a step-by-step approach for testing the use of AR technology in space. They chose a fairly simple application scenario to test the concept's validity: 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 solution to a content delivery system, and the identification of opportunities and limitations of AR use in this context. We based the content delivery on an existing VR system. All information displayed was in the form of 3D geometry, modeled as a whole or in part beforehand. Together with developers in the client group, we developed an entire wearable AR system consisting of a rugged backpack computer, a modified commercial off-the-shelf head-mounted display (HMD) with optical see-through capabilities (Sony Glasstron), and an ultrasonic/inertial tracking system. Although we originally intended this system to display 3D content, we ultimately settled on 2D content aligned to 3D space (see Figure 1a).

We successfully demonstrated the system 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 withstanding extreme operating conditions (for example, 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 enables quick and precise analysis of the engine's state, the accompanying information is still found on a dedicated PC or on printouts. 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 display of diagnosis results in immediate proximity to the engine.

We must address several important questions, however, in applying AR to this process. What kind of information is useful, and should it be represented? What are the technological alternatives available for solving this? If the data are 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 (an eight-cylinder SL model) engine. Again, we used an HMD-based solution connected to a portable PC (or a notebook computer). We used a marker-based approach to track the user's position and orientation. In this case, we attached markers to a U-shaped object, which we placed into a location near the engine (see Figure 1b). The use of multiple markers at well-defined positions provided us with reasonably precise tracking.

We presented the following data types:

- maintenance and repair instructions taken from the garage information system, represented as textual and pictorial information in space;

- prerecorded video instructions in the form of a virtual TV set placed at a fixed position in space;
- 3D models with predetermined animated sequences as overlays; and
- a video/audio link to an expert technician to provide remote technical assistance displayed with the TV set approach.

While the choice of computer and display technology is straightforward, taking into account such matters as cost, design quality, and reliability, the information provision is a bigger challenge due to various key factors:

- The appropriate information has to be selected automatically out of the existing information system (normally text and graphics with references to 3D models).
- The user interaction has to be supported in an easy-to-use way.
- New multimedia content (especially video and 3D models) has to be created and edited.
- The multimedia information has to be brought into a spatial relationship with the object (engine).

This entire authoring process is currently subject to research and development and clearly deserves stronger attention.[6]

Tram diagnosis

Trams (streetcars) as well as other forms of public transportation are large objects with widely distributed technological components, such as wire connectors, relays, fuses, and electronic units. The interplay of these components is complex and the maintenance of the entire system requires skilled technicians and highly developed diagnosis systems. In addition to the car maintenance example mentioned previously, two main challenges exist in maintaining trams:

- An AR system needs to be wearable because of the distance between the components.
- An information system linkage to the existing diagnosis systems is mandatory for maintenance to occur.

We developed and tested a back-worn wearable AR system incorporating a modified notebook computer and all peripheral components for a self-contained video see-through system 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 text.

While the system as a whole works well in our laboratory setup, a real-world application is unlikely in the near future. The main shortcomings of the approach are

- The instrumentation of the environment for tracking purposes is unacceptable. Neither fiducials nor other mounted sensors are practical.
- The wearable unit is too heavy (approximately 6 kilograms) to use for extended periods.
- 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 (for example, servicing) or the support of manufacturing processes (for example, assembly instructions) is an obvious option. One often-overlooked opportunity, however, is supporting the product design and development process. 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 using physical and digital mock-ups. While the geometric properties—for example, seat placement, compartment lining shape, kitchen appearance—can be simulated quite well, some physical property simulations—like temperature, speed, and cabin air flow direction and pressure—are more complicated. The implementation of a physical mock-up simulating these properties is complex and not cost-effective.

The visualization of computational fluid dynamics (CFD) data in the form of voxels (volume pixels) is a common way to overcome having to use a physical mock-up simulation. For instance, a high-pressure value at a certain location in the cabin is visualized as a small yellow cube, a point of low pressure is visualized in red. The entire visualization of, for example, 128^3 voxels looks like a colored cloud and can help interpret cabin comfort. This interpretation is difficult if the spatial reference to the real environment is missing (for example, displayed on a monitor). AR allows for the combination of the real space, that is, the cabin, with the CFD data sets.

We have integrated a self-contained AR system powered entirely by batteries into a flight attendant's trolley. The user's position and orientation is tracked with temporarily placed 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 used a VR system as a basis for the AR system, the solution is suited for digital mock-up displays as well. This system can supply 3D visualizations of elements of the cabin that have not yet been built; 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. We need to make the HMD more robust and give it a more ergonomic design, improve the update rate and robustness of the tracking system, and improve access to CFD and 3D model data.

2 Overlay of computational fluid dynamics data (clockwise): cabin, CFD only, CFD and phantom model, and 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 account for all requirements and to find the best solution. This is a collaborative task by nature, because the decision-making process is far too complex for a single person to accomplish. Frequent meetings with specialists are the most common method of making design decisions. These meetings incorporate digital data (for example, CAD models) as well as physical mock-ups and rapid prototype models. The construction of physical component models is time-consuming and expensive. AR 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 appearing to stand on the table.

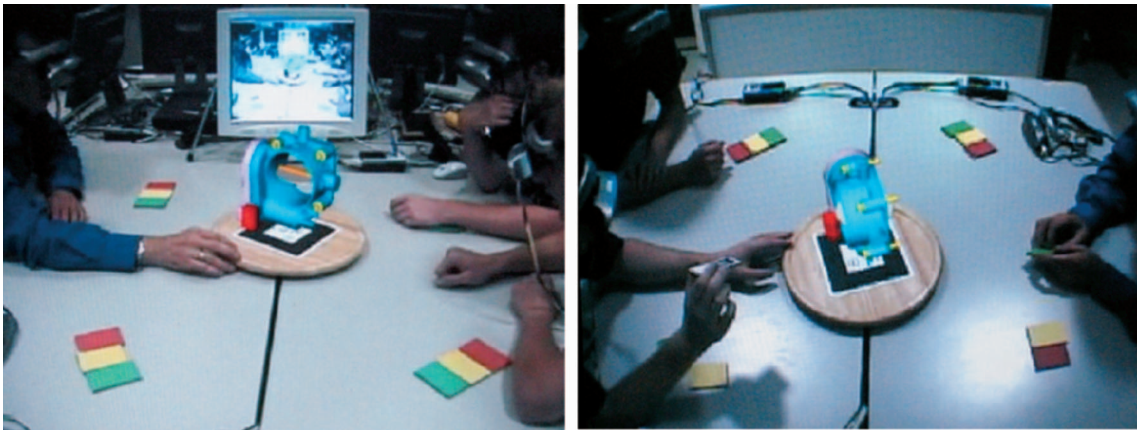
Our prototype system enabled four people wearing HMDs to have such a meeting (see Figure 3). We virtually place the object on top of a turntable—a rotating board (cake platter or lazy Susan)—which serves as a tangible interaction device. A more detailed description of the system is available elsewhere.[7]

Besides the need for further development of the system toward a more efficient usability, the main remaining research and development tasks are

- a tighter, more integrated link with the existing product data management systems; and
- the development of a way to visualize large and complex data sets.

Cockpit layout

The huge number of displays and controls in an airplane cockpit requires a careful design that considers many issues including functionality, ergonomics, and safety. It's helpful in the early design phases 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 let the designers experiment with different arrangements and to annotate each of them. Figure 4 (next page) shows an



3 Meeting incorporating a virtual engine part.

4 Early phase of cockpit layout.

inside view of the system, which is described in detail elsewhere.[8]

When lighting conditions are set carefully, the system is reasonably robust and easy to use due to the interface tangibility. The combination of HMD and monitor display options makes for a flexible interface. 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 early design discussions and could be extended to other tasks or phases only with significant further research and development.

Production support

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

Given the requirement of providing a value-adding AR application, the identification of a suitable workplace is difficult. AR technology at this stage of maturity is not robust enough to apply to the whole manufacturing process. Together with internal and external specialists (see http://www.ar-solutions.de and http://www.shared-reality.com), we have identified some application scenarios where AR could be applied successfully and could gain a reasonable return on investment. Here we present three such potential applications in order of increasing technological complexity that illustrate the different stages of maturity.

Fuse placement

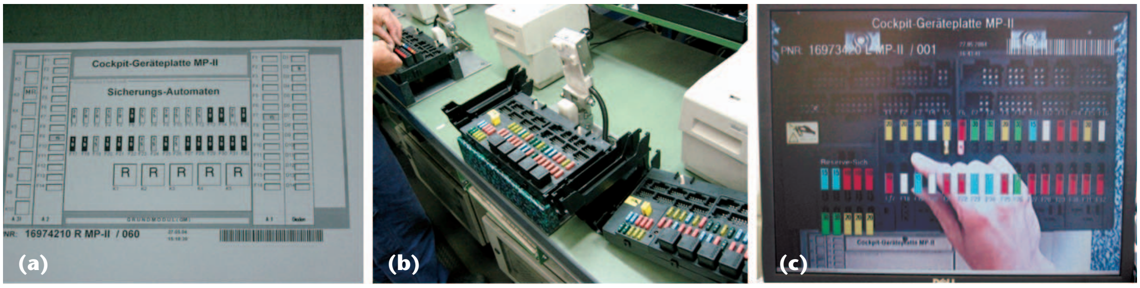
In the truck manufacturing example considered here, no two trucks are ever really identical. The variety of options available to customers is wide-ranging. Because of the many possible combinations of these options, virtually every truck that leaves the plant is unique. This can be observed, for instance, with the placement of fuses and relays for the truck cockpit. According to a black-and-white schematic printed on paper (Figure 5a), a worker inserts fuses manually into a board. The various types of fuses are represented by numbers on the schematic (for example, 15 means a red-colored fuse). Figure 5b shows the working environment. The board is brought into a fixed position on the table (and is connected to a control unit that sets the internal parameters of the board's electronics) where the operator manually installs the fuses.

Because of the board's fixed position, 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. Figure 5c shows the overlaid image.

This example shows how a simple solution could be found because of the environment's AR-friendly nature, giving a robust, value-adding solution. This prototype is about to be introduced into the Mercedes truck production process.

Picking

The process of picking can be described as manually seeking a particular item in storage according to a list (see Figure 6a), 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 the case of 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:

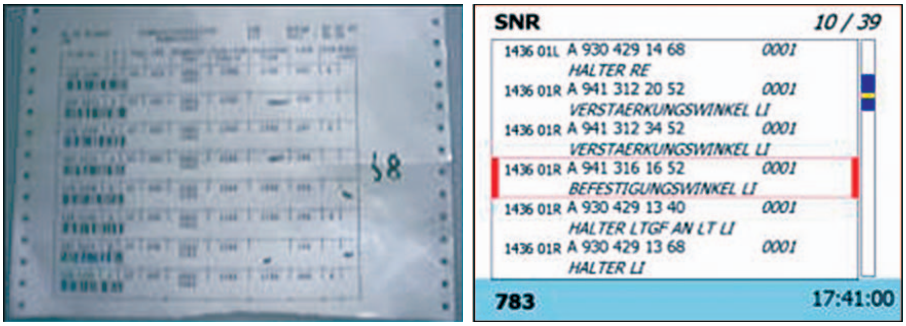


5 Truck cockpit fuse and relay placement: (a) fuse plan, (b) worktable, and (c) augmented view.

- error reduction, that is, reducing the number of errors in reading from the list and reading the labels of the items in storage, and
- savings in the time taken to travel between different storage locations and to and from the transport cart with the list attached to it.

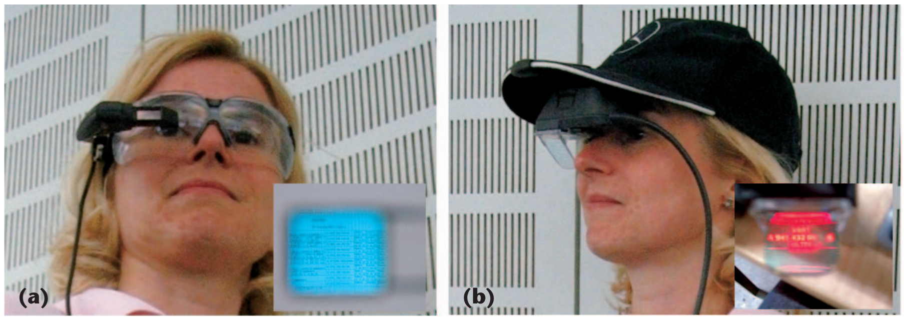
After assessing the merits of several AR approaches, we eventually decided on the implementation of an untracked, optical see-through HMD. This method brought list information to the worker in a more robust and failure-minimizing way (see Figure 6b for a list example).

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



(a) (b)

6 **Picking list: (a) on paper and (b) in viewing device.**



7 **(a) Microoptical display and (b) nomad display.**

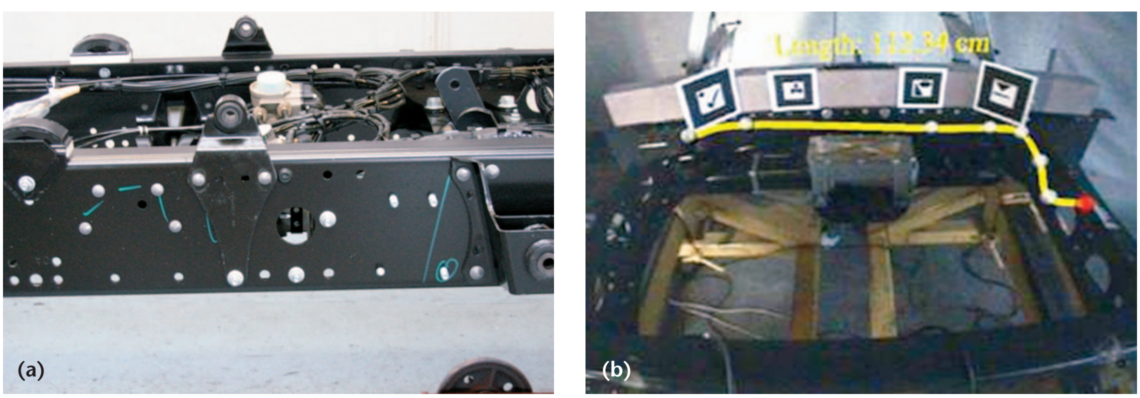
The main challenges with both system approaches are

- the failure-free and instant provision of the data to be displayed,
- the form of interaction (changing list items, changing lists, confirmation and abortion of actions), and
- 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, semiautomated 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 AR approach where virtual wire bundles are laid into the real geometry (in this case the truck's girder) with on-the-fly data transmission to where the wiring bundles are constructed.

We introduced and compared different hardware technologies involving combined active and passive optical tracking, an HMD, a large monitor, and projection technology in combination with a software solution developed especially for this process. Figure 8a shows a truck chassis section with wire bundles; Figure



8 **Girder (a) without and (b) with augmented wire bundles.**

9 (a) Driver and trainer wearing HMDs and (b) augmented scene.

8b shows the overlay of a wire bundle (in yellow) with mounting points.

While the software was well received by the users, it has two main shortcomings. First, the tracking systems used require too much instrumentation of the environment and are too sensitive for the harsh environment (lighting conditions, vibrations, possible collisions with objects or persons). Second, 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 (for example, a laser).

Although Mizell applied AR in a slightly different context (wiring on boards distant from the actual production line), he came to similar conclusions.[1] 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 VR or other multimedia 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 can imagine many possible training scenarios in different fields. We present here a more exotic scenario to illustrate the possible scope of AR applications.

Driving a car is a complex task requiring car-handling skills, road rule knowledge, and driving experience. While the vast majority of drivers master standard traffic situations well, unexpected events and adverse environmental conditions are always challenging and sometimes create dangerous situations for the driver. This is still true today even though today's cars are equipped with innovative assistance systems. An antilock braking system, electronic stability program, and active body control, for instance, are safety systems found in modern car specifications. Even if drivers are familiar with the underlying principles of these systems, they might 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. For instance, a situation simulating a child suddenly jumping onto the street can be done only with abstract substitutes (for example, throwing an object onto the street manually). AR 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 driving. Both the trainee and the trainer wear HMDs with video see-through capabilities (see Figure 9a). Notebook computers located on the back seat deliver the virtually overlaid content (see Figure 9b). The current tracking uses a combination of fiducial and inertial systems. Together with the customer (the safety program agency), we have developed a number of driving scenarios and implemented them using standard VR and animation tools.

From our customer's perspective, this application is clearly seen as value adding to the existing programs. The trainees react in a similar way as to real scenes, illustrating the effectiveness of the augmented content. We will reengineer the system for quality improvements and multiple deployments.

Lessons learned

There are many technical and organizational issues to resolve before we can apply AR in the field. Besides the application-specific issues addressed here, some general guidelines can already be drawn from the experience we have gained. Even those might 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

AR researchers often seriously underestimate the effort required to incorporate real-world data into the AR application. Most demonstration scenarios work well with (manually) preconfigured 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. We could 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 carefully with key persons in innovator roles. These people should work as closely as possible with the researcher, know the application field well, and be widely accepted among their colleagues to serve as a point of multiplication for later dissemination. If a project does not have 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, and so on) is laborious but worthwhile. Additionally, usability studies with representative subjects should be a part of every application project.

Finally, if researchers have 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 set up 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 true for industrial AR projects. From the researcher's point of view, the best solution might not be the one with the highest level of originality or novelty. Imagine if 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's 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. Researchers have 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, such as cost, quality, time, and knowledge gain, helps and often enables starting the project. Even if the data 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 AR researchers, but they will still be concerned with these issues. Ideally, a project team can find experts in the field of industrial economics to provide appropriate data or estimates.

In a midterm perspective, AR is on its way to becoming a productive tool in industry. The spectrum of application fields is 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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