Cognitive, Performance, and Systems Issues for Augmented Reality Applications in Manufacturing and Maintenance

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Abstract

This paper presents cognitive studies and analyses relating to how augmented reality (AR) interacts with human abilities to benefit manufacturing and maintenance tasks. A specific set of applications is described in detail as well as a prototype system and the software library its built upon. An integrated view of information flow to support AR is also presented along with a proposal for an AR Media Language (ARML) that could provide interoperability between various AR implementations.

1. Introduction

The media form presented by AR is complementary to human cognitive processes. Potential benefits to users of AR can be analyzed by reference to effects in cognitive psychology in the areas of information access, reduced error likelihood, enhanced motivation, and concurrent training and performance. A simple application will illustrate these areas and lead to a discussion of an AR software organization. Manufacturing and maintenance tasks are the focus in the analysis and in the application.

2. Augmented Reality as a Complement to Human Cognitive Processes

2.1. AR Information Access Integrates Retrieval and Human Performance

An augmented reality can trigger the appearance of virtual objects by the user's view of real equipment and structures. For example, in one application study, the act of looking toward a workpiece allows electrical workers to see wiring harness assembly instructions (Caudell, Mizell 1992). This dynamic is very different from technicians' typical interaction with information about equipment. Normally, the information is detached from the equipment, except in the case of control panels and where lighting, frequency of use, and the size of parts allow physical labels or tags to be glued or tied to them. The worker searches a medium (e.g., paper manual, microfiche, laptop computer) for information, often in the form of an annotated drawing or photograph. AR can spare the worker the search. The act of looking at or directing a camera at the equipment is sufficient to produce information.

It may seem obvious that eliminating the search for information would benefit a task. However, there is a long and accepted tradition that retrieving information in some detached medium (usually paper) is a normal part of tasks; the two types of activities--informational and workpiece related--are so connected that it is easy to overlook the impact of informational activities on workpiece performance. For example, "aircraft maintenance" evokes images of repair actions on actual hardware, but an airline spokesman reported that 45 percent of every technicians' shift is actually spent on finding and reading procedural and related information (Ott, 1995). Of course, observation can reveal that tasks involve different activities. From a cognitive standpoint, the skills and abilities invoked for these two requirements are very different, and they

Table 1. - Typical classes of activities in the informational and workpiece portions of maintenance and manufacturing tasks

Informational portion	Workpiece portion
· Direct attention to storage medium	· Direct attention to workpiece
· Read, comprehend, interpret, calculate	· Inspect, discriminate, compare, select, align
· Understand speech	· Orient to sound, interpret sound
· Form hypotheses	· Adjust or actuate devices, detect movement
· Transpose information from documents to workpiece	· Manipulate devices

are often invoked sequentially. Table 1 lists typical activities in each domain. The distinctions implied in the table are often blurred, but in general, document-related activities tend to be cognitive, workpiece activities tend to be kinesthetic and psychomotor, and both involve visual and auditory factors.

The workload literature distinguishes among types of activities according to the effort or amount of resource required for them. For example, in the U. S. Army Task Analysis Workload (TAWL) system, seven levels of demand for attention are described for each of five human abilities (cognitive, visual, auditory, kinesthetic, and psychomotor) (Hamilton, Bierbaum, & Fulford, 1991). In the TAWL system, the abilities typically engaged for tasks related to obtaining and assimilating information are found at different levels of demand for attention than are the abilities engaged for tasks with workpieces. Further evidence that searching and other activities related to information are different from workpiece activities comes from Towne (1985). Towne measured the time for two types of behavior in equipment fault isolation tasks: time for actual manipulation of devices and instruments (manual time) and time not engaged with devices or instruments (cognitive time). He found that cognitive time accounted for about 50 percent of total task time. More importantly for our current point, cognitive time was independent of manual time, meaning that individual technicians differed in how much time they devoted to cognitive/informational chores, but differed little in how much time they devoted to manual chores. This sort of relationship between components of a task is often regarded as evidence that different types of attention underlie each component--that they are indeed unique behaviors that are potentially separable and "treatable." We also know by experience and insight that manual and cognitive activities (or workpiece and information activities, as we have called them) generally happen sequentially rather than concurrently, unless they are highly practiced. Therefore, we can conclude that if cognitive activities had been reduced for the fault isolation technicians, their total task time would have been lowered. This is just the sort of benefit envisioned for AR in manufacturing and maintenance tasks.

Finally, the differences between information and workpiece activities indicate that when they must both be accomplished to reach some end, they together qualify as a multiple task performance (Damos, 1991). Rogers and Monsell (1995) have shown that it is easier to keep doing alternate versions of the same task than it is to switch between different tasks, indicating the presence of some overhead chore, such as retrieving "rules" associated with each task. We expect AR to lower the frequency of switching between information and workpiece tasks and therefore to reduce the time and energy demanded in this repetitive switching.

Ironically, many marketing and publicity photographs of conventional (non-AR) head mounted displays (HMDs) try to imply that these products will cause the multiple task performance in maintenance and manufacturing jobs to become single task performance, but unwittingly, these images suggest just the opposite. These photographs often depict a wearable computer and video display that creates superimposed graphics without any regard for registration. The photographs capture the wearer in what looks like a trance-like state, perhaps holding a tool or touching a workpiece, gazing at the display but appearing to be completely detached from the workpiece task. This is exactly the state we would expect if the user must direct attention to a display that is independent of the workpiece. On the other hand, we would not expect the user of an HMD hosting AR to appear detached from the workpiece task because retrieval and display of information is integrated with views of the workpiece.

2.2. Reducing the Potential for Error

When tasks are repeated very frequently, manufacturing and maintenance technicians can become experts in those tasks through the combination of low performance variability and "overlearning." The likelihood of errors is often a function of the interaction of individual factors such as a worker's expertise and situational factors such as the task environment (e.g., Meister, 1971; Reason, 1990). For example, novices and experts are equally likely to err in performance under low stress, but novices are more likely to err under high stress (Miller & Swain, 1986).

AR can endow novices with some of the advantages enjoyed by experts, such as an efficient retrieval of information from memory, regardless of the situation. We believe that AR provides this expert status in two ways. The first is simply the basic effect of AR–the triggering of information with little user effort. Maintenance and manufacturing experience is filled with evidence that people favor information that is easy to access and tend to use more salient data in decision-making (e.g., Yoon & Hammer, 1985). Conversely, technicians resist the effort involved in accessing remote or distant information. In a related situation, information from head-up displays (HUDs) in aircraft has a much lower "access cost" and is therefore more likely to be scanned than is the same information from instrument panel displays just a few inches away (Wickens & Long, 1995).

The other way AR reduces error is by speeding the user's transition from "information novice" to true, unaided "information expert." This transition is facilitated by dynamics of AR that complement human associative information processing and memory. First, virtual objects have locations, and second, virtual objects can be associated with real-world features.

2.2.1. Virtual Objects Have Locations

When a workpiece is viewed (and AR is invoked), both real and virtual objects will inhabit the viewer's scene. Psotka and Pflaging (1995) compared recall for 21 familiar items (e.g., potted plant, ladder) pictured in a series. In a Monitor (Mon) condition, subjects viewed the items on a stationary monitor. In the Virtual Reality (VR) condition, items were programmed to appear as though arranged in a circle, and subjects swiveled in a chair to observe them. In the Augmented Virtual Reality (AvR) condition, items were arranged as in the VR condition, but appeared to be projected on the walls of the experiment room. After viewing, subjects recalled as many items as possible in any order. The AvR condition produced an average of twice the number of items recalled (18.4) compared to the Mon (9.3) and VR (9.4) conditions. The authors interpreted the results as pointing to the importance of spatial consistency of objects relative to the real-world coordinate system. The number of subjects in this study was small, but the outcome suggests a potent memory effect when to-be-recalled items are associated with real-world locations.

There is abundant evidence that it is the nature of attention to work spatially: attention can be conceived as a "spotlight...directed at circumscribed regions in visual space" (van der Heijden, 1996). If we follow that evidence, we would be inclined to conclude that placing virtual objects in the context of real locations makes the objects subject to particular human abilities, and one of the most critical of those abilities is spatial cognition -- an imagery-related ability to know or learn the physical layout of things (Anderson, 1980, p86). Over repeated encounters with a space, people (usually without any conscious effort and probably as an adjunct to attention) build up an enduring, internal representation or "cognitive map" of the space (Thorndyke, 1980). It is plausible that by incorporating virtual objects into real-world scenes, the objects become part of the world scene, as far as attention is concerned, and become spatially defined entities just as other actual elements do. By their incorporation into real context, cues are added to the objects that they do not possess independently of the real context. Miller (1968, cited in Psotka and Pfalging, 1995) referred to these spatial underpinnings of attention with the phrase "People like to know *where* the information is" (italics added).

We believe AR's composite scenes are analogous to the spatial, graphical user interface (GUI) that now dominates computer use. The interface model became the standard expression for desktop use for at least two reasons. First, through direct manipulation metaphors, it eliminated users' need to control functions via arcane textual language, and second (and especially relevant to AR), its desktop metaphor presented a spatial layout to the user--icons and working spaces can occupy regions (often called "real estate") of a display. The GUI allows users to associate functions with spatial locations, it aids visual recognition (e.g., "similar look and feel" of various applications), and it elicits behavior, such as dragging and interacting with buttons.

AR by definition presents a visual-spatial dynamic to the user, so we can expect the human performance advantages associated with GUI's to also occur with AR scenes. For example, Hess and Detweiler (1995) reported that subjects who must keep track of a running stream of inputs are "particularly helped when each item is associated with a unique and constant location in space." That is, subjects can recall, in order, more items and integrate the meaning of a string of items when the items simply and merely have a consistent spatial origin. Therefore, equipment-related tasks that are normally guided by reference to some documentation may be excellent candidates for improvement with AR. This opportunity occurs because virtual callouts that appear in places within the workpiece scene may be attended to in ways that incorporate location, and to the degree that callouts are consistently positioned in workpiece scenes, the positioning (apart from any content) will aid the user's organization of information.

2.2.2. Associations Between Virtual Objects and Real World Features

In addition to the relationship between a virtual object and a spatial location described above, the content of an object (e.g., its text expression or its shape) can be associated with a workpiece feature. AR creates a framework of associations that aids recall and learning. Each association of a virtual object with a workpiece feature is the basis for a link in memory that might not otherwise exist. These links together (e.g., an array of callouts in a workpiece scene) may form a framework like that created when subjects use a classic mnemonic technique, called the method of loci, to remember a lists of items. With this method, a subject associates items to be remembered with invented places or landmarks on an imaginary path (Yates, 1984). During recall, the subject "mentally walks" on the path; and as he or she encounters the landmarks, the item associated with the landmark also appears, and is therefore available to working memory. With AR, a technician is provided with a framework--the real world--which can also hold the items that will be recalled. Association and elaboration do not necessarily happen intentionally; they can occur as a by-product of the use of enhanced workpiece scenes in production work (cf unintended processing in Fodor, 1983, and Stroop, 1935).

2.3. Enhanced Motivation

Multimedia can produce a rich sensory experience that not only conveys information, but "...appears to increase the motivation and interest of the reader or viewer," as Chignell and Waterworth (1997) stated. A serious question is whether AR media could be designed to engage a user in a task with even a degree of the effect that some multimedia can produce. Can the media--apart from its informational value--be compelling enough to become the technician's preferred tool? Could the media increase compliance to correct procedures? Veinott and Kanki (1995) found that in the Aviation Safety Reporting System (a NASA-conducted method for airline personnel to report problems anonymously), 60 percent of maintenance-related reports concerned procedural errors, and many of these errors were due to negligence. Also, negligence and bravado played a big part in a forest products company's high injury rate (Fisher, 1997). The point these examples illustrate is that some deficiencies in maintenance and manufacturing are not due to lack of information. We believe that AR is a candidate to produce better adherence to correct procedures by virtue of increasing motivation. Today, the technology creates a basic multimedia experience for the user, and in time, virtual objects in AR will take on more roles, be more smoothly integrated into the real-world scene, and offer greater interactivity.

Because the computer-generated overlay is under program control, there are many choices to increase the interactive, engaging, multimedia aspects of AR. A virtual object, for example, can be a symbol, video/audio clip, query to the user, menu, CAD solid model, synthetic instrument face, communication window, input button, agent icon, or any other object presentable by computer. The options are nearly limitless, and are set up by the planning and authoring stages in an AR system development. Some of the potential uses of this control are listed below.

- Design objects to influence the user's focus of attention (e.g., cautions or warnings).
- Enhance user's ability to organize (parse) elements into functional sets (e.g., overlay color coding on pipe runs).
- Design objects to be adjustable (e.g., to appear more or less distant from the viewer, or to provide text in different languages for multicultural crews).
- Make objects dependent on operating conditions (e.g., higher contrast callouts in bright viewing conditions).
- Allow users to invoke a virtual “copy and paste” to keep information accessible (e.g., to reduce the need for "reinstatement" searches (Wickens & Carswell, 1997)).
- Improve operator's ability of discriminate (e.g., Wong & Otsubo (1990) showed that a simple grid over a video image of the Shuttle Remote Manipulator System (RMS) was a great aid to judging whether or not the RMS was moving).

Table 2. - Human and Machine Information Activities in an Unfamiliar Inspection Task

Human Abilities	Augmented Reality Annotations
· Detection of meaningful stimuli and patterns. · Integration of information within and between modes (e.g., sight, sound, and smell as indicators of condition). · Comparison to standards. · Qualitative judgment.	· Attachment to workpiece eliminates need to search for information. · Images that are examples of correct condition. · Markers or flags that direct attention to specific workpiece features. · Annotations that influence inspector's anticipation, such as knowledge of expected defects. · Input methods so inspector can obtain the level of detail he or she needs for particular workpiece features. · Easy-to-use interface for recording and reporting inspection results.

2.4. Concurrent Training and Performance

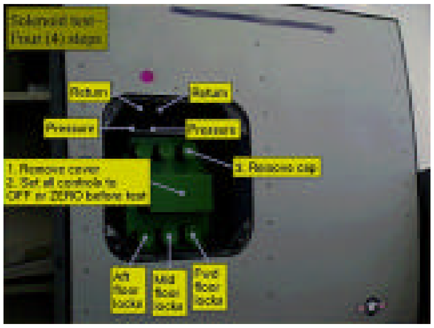
Training has multiple purposes, but we focus here on the objective of providing information necessary to perform tasks. People are often trained with some approach (e.g., computer-based training, classrooms with paper manuals, etc.) and then assigned actual tasks. With on-the-job (OJT) training, more experienced workers provide trainees with a flow of guidance and information until they can work independently. Distance learning, wearable computers with head-mounted displays, and shop floor computers have been implemented to reduce training needs.

All the methods above can be successful. However, we believe that the state of the training art can be advanced with AR because of the technology's unique characteristics described earlier. In fact, we believe that AR can make some forms of training unnecessary, or at least greatly reduce the need for training as a distinct process. When cognitive tasks normally associated with training are carried out for the human by an AR system at the point of application, it becomes possible to design training functions that are just-in-time or are enacted concurrently with tasks. For example, during equipment inspection, the value of the human making an inspection is the application of unique human abilities to the examination of processes or objects. These are abilities such as detection of meaningful stimuli and patterns that are too difficult or too costly for automated systems to detect, the integration of information within and between modes, comparison to standards, and qualitative judgment. One objective with AR might be to provide scenes that are annotated with types of information that are normally acquired through training and, in essence, support humans in inspection tasks or enable them to apply unique abilities to tasks that are novel or so rarely encountered that little prior training is provided for them. These capabilities include obtaining information, domain expertise, appropriate expectancies or mental sets, procedural knowledge, and reporting methods. The allocation of functions for "just-in-time" training for an exemplar inspection task are shown in Table 2.

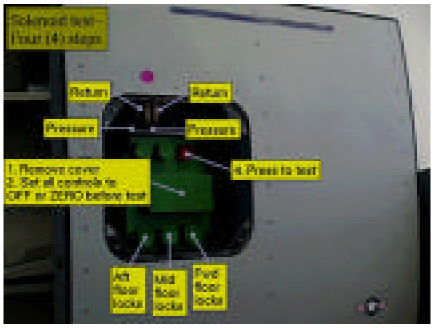
3. Aircraft Maintenance Simulation

This section describes a maintenance scenario that has been implemented based on AR media. A mockup of a portion of a transport aircraft is shown in Figure 1 with varying annotation that is generated in response to the state and context of a simulated maintenance procedure (Fig. 1, plates A, B, C, D). The mechanic's task is essentially to test circuitry in an

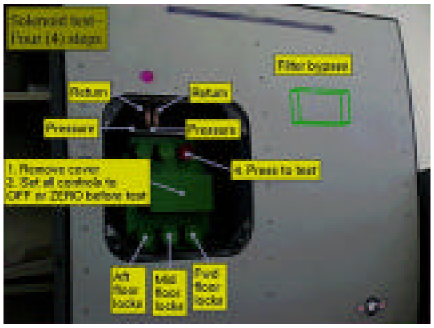
(A) Identification of ADS manifold access panel



(B) Recognition of open panel causes identification of components and instruction to remove cap



(C) Recognition of cap removal causes new instruction to press button



(D) Additional information about position of occluded filter bypass structure in response to user's query

Fig. 1 - Sequence of automatic instructions and information for maintenance task

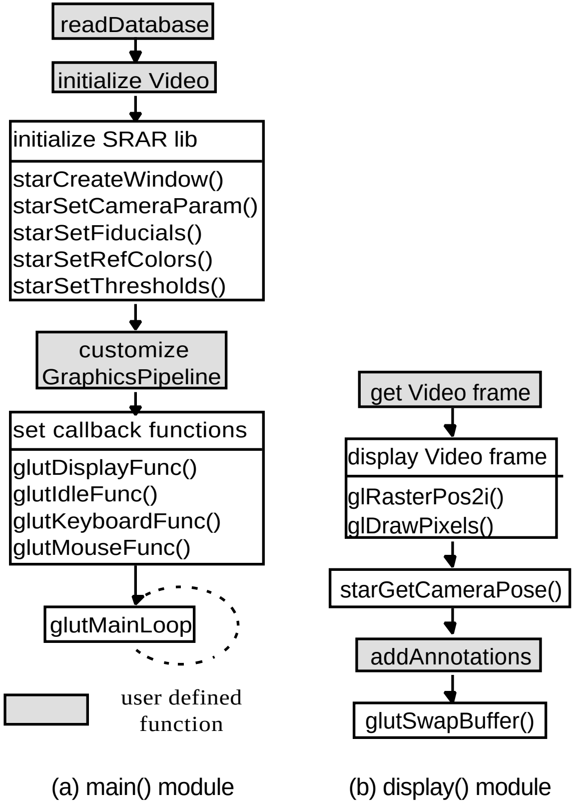
electro-hydraulic manifold. The task sequence exemplifies several of the benefits of AR that were previously described:

- In Plates A and B, annotation appears solely as a function of directing a camera at the workpiece, so easy access to information increases the chance that the information will be used. Virtual objects are spatially arranged in the task area, and each has a location that is constant for a particular view. In all cases except the "Solenoid test" callout, the content of the virtual objects is associated with features of the workpiece by connecting a line segment between the object and the feature, and by locating the object close to the feature. People who have viewed the scene report that it elicits attention.
- In Plate B, virtual objects relate task information (a 4-step solenoid test is being performed), to the context of the work area (callouts identifying locks and hydraulic lines), and guidance on the next action to be performed (remove cap or press to test). The design of the scene is intended to reduce error by (1) influencing attention and (2) supporting users' encoding (learning for later recall) of layout and content.
- In Plate C, the AR system senses the state of the assembly (the user removed a dust cap as instructed in the Step 3 callout) and responds automatically with a new instruction ("4. Press to test"). Therefore, the content of the array directs performance and the interactivity inherent in the system's production of a new instruction will contribute to the user's motivation.
- Interactive queries are indicated by mouse selection of an area (Plate D) in order to reveal and identify additional hidden structures related to the task. This form of interaction demands that the user attend to his or her view of the workpiece.

This application is implemented using an AR software development library (STARlib1.0) that is briefly described in the next section.

4. Summary of STARlib

STARlib is designed to simplify the creation of AR media demonstrations and pilot applications, and enables the developer to create augmented scenes that are responsive to the dynamics of human information processing. The system is based on OpenGL, glut, and a video input library. It currently runs on 24-bit color SGI Indys. A color video camera observes the world and the images are analyzed to detect colored stickers or fiducials. These must be present on the workpiece in the regions of interest. When three or more are visible in the camera's view, the system attempts to recover the camera's pose. If successful, the application program is provided with the view transformation and it may render annotation data onto the camera image. Since the video image is also available to the application program, it may also analyze the image to determine the assembly's state, for example. Additional details on the internals of a previous version of STARlib can be found in Neumann and Cho (1996).



(a) main() module (b) display() module

Fig. 2 - Software structure of Starlib showing user-defined functions in relation to program modules

Application programs use Starlib in a straight-forward manor that is outlined in figure 2. User functions in the `main()` program completely manage the annotation database and initialize the graphics rendering process based on OpenGL or other rendering library. A callback function, `display()`, is the glut idle function, and this is where user functions for acquiring video frames, image analysis, and rendering the annotations are invoked.

5. Authoring and ARML

Few AR systems have moved beyond laboratories to deployment for application and user evaluation. For AR systems to become widespread, technical hurdles must be overcome, particularly in the area of object-centric tracking. Workplace acceptability will also be an issue, and the practical issue of content creation and interoperability must be addressed. Widespread media usage (*e.g.*, CDs, VHS tapes, HTML, and VRML) is enabled by formats and standards that pose few constraints on content or purpose while supporting a range of play-back system implementations, each with their unique technologies and quality of reproduction. Even with a very limited number of Starlib users, it has become clear that an AR media language (ARML) is needed so that application content can be authored without regard for which AR display version or technology will be available to a user.

Figure 3 illustrates a possible approach and organization for ARML. Data extracted from CAD models or direct measurements provide the essential geometric coordinates for points of interest on the workpieces. Complete geometry is not needed so CAD models remain the property of their owners. Content authoring involves creating the media (text, models, images, etc.) that is appropriate to the training or manufacturing task. The media must be linked spatially to the geometric data and temporally to the state of the workpiece or a fixed sequence. These links may be static, set during authoring, or varied under the control of the AR application program at run-time. Individual workpieces (or regions of a large assembly or building) may be identified by unique IDs that are related to the geometry data or encoded as part numbers or bar-codes. Object IDs allow the AR application to behave differently for each unique object. Features provided for calibration and tracking are also described for each object and ID. Feature descriptors should include coordinates and characteristics that help the AR system locate and use them. The combined geometry, media, IDs, features, and application programs are bundled into an ARML data format that can supply the needs of a variety of AR display or tool implementations.

The modes whereby the ARML components are delivered to the AR display may vary and be application dependent. For example, a wireless hand-held AR display may have a CD-ROM drive that provides all ARML components. Alternatively, a flash memory may contain generic ARML components that apply to all structures and assemblies, and additional components, unique to a specific workpiece ID, are loaded through an IR-link from a database containing ID-specific media and program updates.

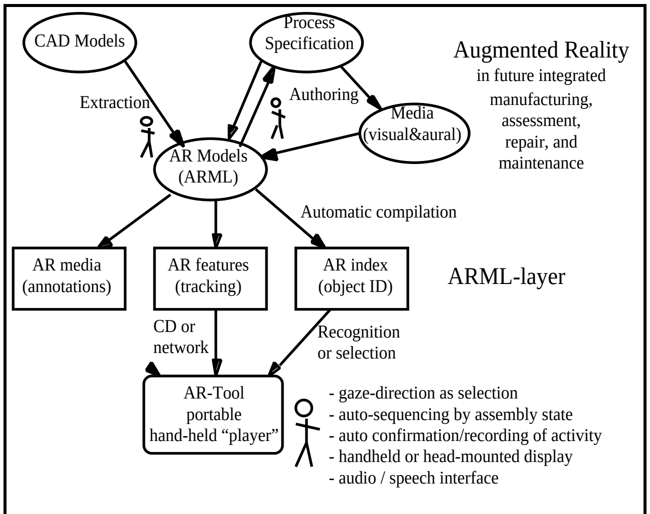


Fig. 3 - Participants in generating and deploying AR media

Many current data and program formats, already adopted for other purposes, are likely candidates for use in ARML. VRML encodes 3D geometry and interaction behaviors. JAVA is designed to provide a secure program for a virtual machine. HTML encodes arbitrary graphs of relationships between media components. We conclude that the time is right to start working on this problem. Starlib currently uses a very simple ARML subset which allows users to specify a few simple forms of media and tracking features. Object IDs are not yet supported and the application is compiled rather than run-time loadable in the spirit of ARML.

6. Summary and Conclusions

We related a number of features that make AR particularly attractive as an information technology for manufacturing and maintenance. Sufficient data is not yet available to arrive at any conclusions, but the potential appears promising and worthwhile. It is also worth noting that what little experimental data has been collected tends to support the descriptions of machine and human processes in this paper.

We described and showed sample output from an application simulation that is based on a maintenance task for a transport aircraft. The application illustrates the potential strengths of presenting AR information for such tasks. The application has not been tested with real crews since the task we simulated is relatively specialized and simple. Our current work-station and camera AR implementation is also too cumbersome to move in and out of aircraft easily.

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