# Virtual Reality and Augmented Reality for Aircraft Design and Manufacturing

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## Introduction

I am responsible for research and development work at Boeing on two technologies, Virtual Reality and Augmented Reality. I will describe each project, its background and goals, and conclude with some general lessons we have learned from doing VR and AR research and development in an industrial environment.

## Virtual Reality

It is generally known that the Boeing 777 is the first aircraft completely designed using 3D solid geometry CAD. It is also the first aircraft we have designed without using a series of full-size, high-fidelity design models called "mockups," relying on visualization of the CAD geometry instead. Overall, the use of 3D CAD on the 777 project has been a great success, and every aircraft design or redesign that Boeing undertakes will certainly be done using this technology. However, the absence of mockups makes certain design tasks more difficult, particularly those in which a person needs to physically interact with the aircraft, such as to reach around some obstacles and determine if a certain part can be removed by a mechanic performing maintenance on the aircraft. The overall goal of Boeing's VR project is to give the aircraft designers the ability to visualize and interact with an "electronic mockup," one with which they can solve complex design problems and analyze reachability and maintainability without the delays and costs inherent in constructing mockups. Thus, the orientation of our project is that of importing the CAD geometry of some section of the aircraft design into our VR system, and letting a designer both visualize and physically interact with the virtual parts in a manner similar to the way designers formerly used the mockup.

The most challenging technical issue regarding using VR for aircraft design in this way has as its basis the overwhelming complexity of the CAD design of a large vehicle such as a commercial aircraft. Airplanes contain millions of parts, and the CAD representation of each part is extremely detailed, because ultimately it becomes the geometric manufacturing specification for that part. While most virtual environments now being used or demonstrated are geometrically represtented for computer display by several thousand polygons, a complete aircraft CAD design would consist of billions of polygons. Most of the subsets of the aircraft design needed for useful design work would be smaller than the entire aircraft, of course, but would still contain many millions of polygons. Rendering geometry of this complexity at VR frame rates is a tremendous challenge.

Several approaches to dealing with this amount of geometric complexity are being experimented with at university and industrial labs. They summarize to two general approaches: strategies for eliminating parts which will not be visible in a given frame, and strategies for simplifying the geometry of the parts which are visible, but are perhaps far enough away from the viewer that their details wouldn't be visible anyway. Successful employment of these strategies can significantly reduce the load on the rendering hardware of the computer being used to generate the VR graphics. At Boeing, Karel Zikan and Henry Sowizral invented a highly parallel example of the first strategy. It forms the basis of the renderer in Boeing's proprietary VR software system, "RealEyes."

More recently, we have been addressing collision detection. This is the computation necessary to determine if a person attempting to physically interact with the CAD geomtry, such as to grab and move an aircraft part, has caused some part of his/her body to touch some virtual object. In particular, if we wish to use VR to assess whether a given part can be reached and removed by a mechanic, we need to inform the VR user whenever he/she has collided with an obstacle. This is another algorithmic problem which is burdened with the geometric complexity and large number of the CAD parts. On-the-fly surface-to-surface intersections must be computed as fast as the user can move his/her arm among the virtual aircraft parts.

Our goal for 1996 is to demonstrate a first implementation of what we call the "Egocentric Human Model." This amounts to a geometric model of a human body, inserted into the CAD geometry of the aircraft design, which is slaved to the movements of a user wearing several position/orientation sensors on his/her body, as well as a VR head-mounted display. The user sees him/herself inside the aircraft design in first person, and can grab and move aircraft parts and be informed of collisions with obstacles, while perhaps several other engineers observe the interactions from a third-person point of view, by watching the animated mannequin interact with the aircraft geometry on a large, 2D projection display.

## Augmented Reality

In 1990 my colleague Tom Caudell conceived the idea of using a VR head tracker with a see-through head-mounted display to assist Boeing factory workers, by enabling them to see diagrams and text superimposed on the (real) objects they were assembling or manufacturing. The concept, which Caudell named "Augmented Reality," was that if a user could have the locations of his eyes, his head tracker, and the virtual screens of his head-mounted display all mapped into the coordinate system of the workpiece he is dealing with, then the display could show him graphics or text which appears to be drawn on specific coordinates of the workpiece. Because the user's head position is being tracked, as he moves around, the graphics are changed to compensate, and they always appear to be drawn on the same place on the workpiece.

Over the next few years, we implemented several crude prototype see-through head-mounted displays which we used in our lab to develop and test algorithms for registering the user into the coordinate system of the workpiece and for performing the display computations during use. This display and registration algorithm design and implementation was largely the work of my colleague Adam Janin. By late 1993, there was no more work we could do without the help of an electronics company technically qualified to build high-quality protoype AR hardware. Fortunately, at that time, the Advanced Research Projects Agency agreed to fund us in a collaboration with Honeywell Military Avionics Division to prototype and test AR systems.

We have recently completed an application experiment with the first Honeywell prototype AR system, where the system was tested by real users under realistic conditions. We experimentally used the system for wire bundle forming in the wire shop of the Boeing aircraft factory. The traditional method for assembling wire bundles uses an easel called a "formboard," which has a circuit diagram of a particular bundle glued to it. This makes every formboard unique to the bundle which is assembled on it. This means that many thousands of such boards must be stored, incurring storage costs, and that boards must be rebuilt whenever the bundle design is changed, incurring costs, delays, and the risk of rework. In our application experiment, a wire bundle is assembled on a blank formboard. The user sees the circuit diagram information through his AR display. The process seems to be about the same to the user: he sees a diagram drawn on the formboard. With AR, however, the diagram stays digital, and it can be changed at electronic speeds. Furthermore, any formboard can be used to construct any wire bundle.

In our application experiment, we demonstrated that AR can be used to assemble wire bundles. One surprise that occurred was that everyone who built the same bundle using both the traditional method and the AR system was 25% to 50% faster using AR. It turned out that the AR software eliminated some ambiguity present on the traditional circuit diagrams, and thus eliminated one table lookup the worker had previously had to do.

Our goal in this project is to demonstrate that this is a practical approach to providing hand workers better information than they now have, and to convince the companies we are working with, as well as others, that there is a viable market for wearable computer systems, especially AR systems. Our hope is that one or more companies will become convinced that there is a market larger than Boeing for such systems, and will begin manufacturing them and selling them at prices Boeing can afford.

The greatest technical challenge to using Augmented Reality in this way is not rendering, as in the case of VR. Our applications typically display a simple line diagram. The great technical challenge is head tracking: sensing the user's head position within, say, .01 in. and orientation within .1 degree, over as large an area as the worker will move around in while performing some manufacturing task. We have prototyped and continue to develop what is called a "videometric" tracker. In this approach, a video camera is mounted on the user's head-mounted display, aimed toward the workpiece. Simple image processing is used to find fiducial marks on the workpiece. If it is possible to identify each of the fiducial marks in the image, then the user's position and orientation can be computed relative to them.

## Lessons Learned

We have been carrying out research and development in an industrial setting, where the primary requirment is that we produce technology that helps the company -- in the near term. The positive side of this situation is the excitement one feels at being able to significantly improve the way his/her company does business. The negative side has mostly to do with the phrase " near term." Industrial sponsors are not always patient enough to wait until a difficult technolgy has been sufficiently developed for their use. They also never care how clever your technology is. If it doesn't improve their finances, it doesn't interest them. Furthermore, only a few customers seem to be able to "extrapolate," to see your crude demonstration and envision what the finished product will be like. They usually have to see the finished product before they get excited.

Working with industrial customers will always bring surprises. One that we encountered this year was that none of the users of our prototype wearable computers liked using speech input to control the system; all reverted to the alternative of a belt-mounted mouse. We wonder, however, if that had more to do with the relatively poor quality of some commercially-available speech recognition systems than with some fundamental aspect of human nature.

One conclusion I have from leading virtual reality and augmented reality R&D in an industrial setting is that, in this environment, it is difficult to distinguish the "R" from the "D." The invention of fundamental new algorithms and the implementation of demonstration prototypes was always intermixed. Each gave us new ideas for the other. This is actually one of the aspects of industrial computer science R&D which I enjoy the most.