# Augmented Reality in Manufacturing at the Boeing Company

*Lessons Learned and Future Directions*

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# Executive Summary

This report summarizes problems and solutions identified in "Augmented Reality: Development and Implementation for Manufacturing at Boeing," by Paul Davies and David Lee, a case study published by the Boeing Company in March 2014.

Boeing Research and Technology (BR&T) initiated a number of pilot programs exploring usage of Augmented Reality technologies in manufacturing processes at various production sites.

The Boeing studies (describing only projects initiated since 2009) reveal that although Augmented Reality enables technicians to accomplish manufacturing tasks in less time and with greater precision in controlled environments, advances in tracking technology and display device capabilities must be made before the technology can be widely adopted in real manufacturing environments.

# Audience

This report is intended for technical and line managers responsible for implementing Augmented Reality solutions in their organizations. It provides insights into solutions for technical and human issues encountered by BR&T, and assumes general knowledge of IT systems and AR products and concepts.

Lastly, this report is intended for distribution to members of the AREA in good standing.

# Background

As a global manufacturer of fixed-winged aircraft, rotorcraft, rockets and satellites, the Boeing Company has an incentive to explore ways of reducing costs and boosting efficiencies at its manufacturing plants.

Assembly procedures at Boeing are typically published as work instructions, either in the form of paper or electronically as PDFs or other formats.

Because of complex and changing manufacturing requirements, workers must spend a great deal of time in training or in information retrieval while working. The assembly tasks themselves can also be challenging. For example, in some assembly sequences, workers must install parts in a specific order during subsystem assembly. Mistakes from erroneously installing in the wrong order can be costly, as the parts would need to be removed and re-installed in the correct order.

# Objectives

BR&T's objectives for Augmented Reality were to initiate a series of AR pilot programs in three separate locations for evaluation: the Satellite Development Center at El Segundo, California; the KC Tanker Boom Shop and at a plant for the 787 Dreamliner.

The purpose of these programs was to perform internal studies to find systems that would provide robust tracking solutions and handling of 3D objects, while being scalable as an enterprise-wide solution in the future. Over the course of the programs, BR&T evaluated suppliers of software, hardware and motion capture systems.

## AR Architecture

A diagram of the AR architecture (including the AR development platform) used in the case study is shown in “Appendix A: AR Architecture” on page 12.

## Problems and Solutions

The following tables summarize problems encountered by BR&T and describe steps taken in response to those problems.

| AR Development Platform | |
|---|---|
| Problems | Solutions/Workarounds |
| A stable AR development environment providing robust tracking and handling of 3D objects was required, as well as rendering of virtual objects over video feeds.<br><br>The chosen solution should be suitable for enterprise-wide scalability. | • The BR&T team had first contact with AR applications using the marker-based, open-source ARToolKit from SourceForge, and prototyped some applications using this code.<br><br>• The team selected the **D’Fusion** product from Total Immersion, an Augmented Reality software company.<br><br>• D’Fusion was selected for its computer vision capabilities, including the ability to track printed markers, RGB natural features of target objects and 3D objects with a high level of accuracy and reliability.<br><br>• The team used only some, but not all of the features that D’Fusion offered. |

| Tracking and Calibration | |
|---|---|
| Problems | Solutions/Workarounds |
| Cameras must be calibrated to track target objects and virtual content must be aligned onto a live video feed. | Besides calibration of Vicon cameras, the team could create target objects in the Vicon software by computing the centroid of the Vicon markers to create an arbitrary reference frame and attach it to an object. Centroid calculations mimic the object's volume. (See the selection criteria for Vicon Motion Capture Systems below.) |
| Markerless with RGB natural feature tracking (using CAD models) with a single camera was initially attempted for overlaying wire harness routing information on a GPS satellite.<br>*[**Note:** Target assembly had repetitive RGB features at equally spaced intervals along straight lines, while some areas had no features. Stable tracking in some cases while no tracking in others.]* | • Added two fiducial markers to satellite panels to improve tracking stability.<br>• Fiducial markers are not practical in the long term since BR&T does not want to add markers to flight hardware.<br>• As results for marker-based RGB natural feature tracking disappointed, BR&T studied motion capture systems providing accurate, low latency tracking of rigid bodies within large work volumes.<br>• BR&T evaluated two motion capture vendors for providing 6-DOF (degree of freedom) camera pose and selected **Vicon Motion Capture Systems** for its superior tracking in ideal situations, straightforward calibration process and SDK for smoothing the extraction of tracking data (provided in several programming languages).<br>• The team installed an array of eight Vicon cameras (four T10s and four T20s) and placed Vicon markers on target object volumes. |

| Visualization of Augmented Instructions (AD Display Device) | |
|---|---|
| Problem | Solution/Workaround |
| The team needed a device with both sufficiently high performance and durability to endure production and manufacturing environments. | BR&T selected ruggedized tablet PCs of **Motion Computing**. The tablets feature Gorilla Glass and high performance in terms of computing and graphics rendering. The tablets also have two hot swappable batteries to reduce downtime. |

| Ergonomics (Hands-free Usage of AR Tablets) | |
|---|---|
| Problem | Solutions/Workarounds |
| AR tablets do not allow hands-free usage and their extra weight due to ruggedized features caused ergonomic strain. | • The team 3D printed holders for the tablets and purchased **ZeroG** mechanical arms from **Equipois** to hold the tablets in a certain position in order to enable hands-free work.<br><br>• The ZeroG arms were customized to include a quick release interface to allow fast access to tablets when the arm was not required. Adjustable mobile stands were added to increase mobility throughout the work volume. |

| Other Software | |
|---|---|
| Problems | Solutions/Workarounds |
| An interface between D'Fusion and Vicon systems was required. | BR&T developed the core system that handles most computing requirements (calibration functions, scene handling, etc.) and GUI controls, which is then passed to a LUA script, a cross-platform scripting technology based on C. |
| 3D models for natural feature recognition and overlaying on a scene had to be found or created | • The majority of AR projects conducted by BR&T used available CAD files (generated from CATIA & ProE). These files would afterwards need to be appropriately prepared for usage in the AR system (described in the following sections).<br><br>• In rare instances where CAD files did not exist for a target object, the team researched low-cost 3D scanners for model creation, as well as model reconstruction from a Kinect point cloud (the Kinect solution offered a low cost but also low model resolution). Higher-end scanners were available but costly, and were also used to demonstrate a proof-of-concept application. |

| Other Software (continued) | |
|---|---|
| **Problems** | **Solutions/Workarounds** |
| AR systems require polygonised and appropriately prepared 3D models. | • In order to color, animate and alter 3D models, the team used **Maya** from Autodesk, and imported the altered 3D models into D'Fusion with D'Fusion's Ogre3D exporter for Maya.<br><br>• For conversion of CAD files into polygonal format, Maya proved to be too time-intensive and will not be selected for future projects, since procured parts are rarely built according to design specs and designs themselves can change daily.<br><br>• The team selected **Okino Polytrans** for its speed and reliability in CAD file conversion, its usability and price-to-performance value. Okino accepts files from any CAD modeling software (but seems to prefer SolidWorks or ProE) and can handle generic CAD model formats such as .STP, .STL and .OBJ. Okino works with Maya via Polytrans-for-Maya plugin, when Maya is needed for additional file preparation such as coloring, animation, etc. |

| Environment | |
|---|---|
| **Problems** | **Solutions/Workarounds** |
| A work cell for the AR system had to be prepared. | • The first project implementation was done in a large-volume work cell measuring 60' by 40'. The eight Vicon cameras were mounted 15' above the floor and worked well under non-crowded conditions that did not obstruct Line-of-Sight (LOS).<br><br>• Installation work was scheduled during a down period with the help of Vicon representatives and a Boeing maintenance team, and took two weeks due to the project's scale and extensive wiring for the cameras and equipment.<br>**Note**: smaller-volume work cells would not require such extensive preparation. |

| Environment (continued) | |
|---|---|
| **Problems** | **Solutions/Workarounds** |
| There were issues affecting near-infrared light-based tracking systems such as Vicon (e.g., LOS, lighting conditions and reflective surfaces).<br>*[**Note:** LOS issues are caused when working inside of fuselages, underneath large wings, or inside cavities of air- and spacecraft.]* | • A Vicon-type tracking system works well in controlled conditions, but in realistic manufacturing settings, care should be taken to place and aim the motion capture cameras.<br>• In dynamic environments, motion capture cameras should be placed on mounts with the ability to remotely control the cameras' pitch and yaw to avoid timely reconfiguration issues. To offset performance loss due to physical obstructions, extra cameras can be used though this would be costly.<br>• Lighting conditions in work cells and reflective surfaces in camera LOS can cause Vicon-type tracking systems to detect "ghost" or non-existent markers, leading to degraded tracking quality and perhaps failed calibrations. A solution is to carefully aim cameras in a configuration minimizing ghost markers and to run the "camera mask" option prior to calibrating cameras. |

| Introduction to Users | |
|---|---|
| **Problem** | **Solutions/Workarounds** |
| End users must be trained and familiarized with the system. | • BR&T delivered PowerPoint-based training sessions to technicians supporting the AR programs.<br>• A copy of the presentation was saved on each AR display device.<br>• Short hands-on demos for using delivered features were conducted after training. |

## Usability Studies

BR&T worked in collaboration with Iowa State University (ISU), renowned for its Human-Computer Interaction expertise, to improve the user interface of the AR system and ease the transition of AR technology to users.

BR&T performed studies with ISU to determine the effectiveness of AR-based instructions versus traditional work instructions (standard text instructions and PDF documents containing images delivered to a tablet). The study conducted consisted of three groups building a mock assembly of the same wing twice with the same instruction set. The results showed that AR users required less time in order to complete the build and recorded significantly fewer errors during both builds compared to users of the other two instruction types.

Additionally, the AR users required less training time to perform specific build tasks.

## Research into Improved Tracking Methods

Although the Vicon solution worked well in ideal conditions, several factors LOS in manufacturing environments, as well as cost, prompted BR&T to continue to evaluate other tracking technologies. These are detailed below.

### *Shape-based Tracking*

In conjunction with a university partner, BR&T researched the potential for using shape-based (also known as edged-based) tracking using a RGB camera.

Tracking would be based on matching predefined 3D models with color images of target objects using a simple edge-extraction algorithm. Pose would be calculated based on the difference between the two shapes using an error minimization algorithm. This would enable use of a single camera for object recognition.

BR&T is also exploring shape-based tracking using a RGB-D (D for depth) tracker. Depth is used to extract visible edges, increasing tracker robustness. RGB-D devices are costlier and require a GPU, whereas a RGB tracker does not. Both types of trackers are viable.

### *Sensor Fusion*

Sensor fusion combines different tracking technologies to introduce robustness and precision, and enable tracking in all situations.

Sensor fusion compiles data received from multiple sources and passes them through a proprietary weighting function resulting in an accurate pose estimate. The data can be fused in different combinations in order to strengthen the pose estimate from the tracker in all situations.

### *Alternative Technologies*

BR&T also researched magnetic resonance and ultrasonic tracking, which bring costs and benefits that must be compared with other technologies.

## Advanced Visualization and Interface Options

### *Head-mounted Displays*

HMDs like Oculus Rift promise information-rich, hands-free AR experiences but at a cost of degradation of users' field of view (FOV) due to their immersive nature, and are not optimal for busy, cluttered and even dangerous production settings.

Such HMDs could be useful in design and training environments.

### *Wearable Displays*

Wearable displays including wrist-mounted devices fitting onto a user's forearm with curved or flexible displays could be useful for replaying work instruction or tooling tasks.

Such devices offer ease of accessibility and potential for a hands-free system, though also possess limiting factors that may require workarounds to maintain the same level of capability observed with more standard interface devices.

## Conclusions

At the time of this report, Augmented Reality tracking and display technologies are not sufficiently robust for mainline manufacturing production environments.

Advances must be made in tracking objects in 3D volumes that allow for 6-DOF tracking in all environments without relying on external sensors.

More research is needed to find potentially immersive display technologies offering wide FOV, wireless capabilities, and comfort and safety of use for long durations.

## Appendix A: AR Architecture

The AR system described in this case study is shown below.