

## Evaluation of Optical See-Through Systems

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### ABSTRACT

In an optical see-through Augmented Reality (AR) system, such as an inspection assistant, it is important that the registration between the real and virtual objects is within a specified tolerance. This requires careful calibration of the system components and a way to evaluate this calibration. Currently, there are no online methods capable of giving a quantitative evaluation of the calibration accuracy for an optical see-through system.

This paper describes a method for measuring the registration accuracy for an optical see-through system. This method provides quantitative measurements as well as information on how to correct the current calibration of the optical see-through system.

### 1. INTRODUCTION

In order for an augmented reality system to be effective, the virtual objects must be accurately positioned relative to the real objects. This implies that certain measurements or *calibrations* need to be made. These calibrations determine the transformations between the various components such as trackers, cameras and HMDs. What needs to be calibrated in an augmented reality system and how easy or difficult it is to accomplish the calibration procedure depends on the architecture of the particular system and what types of components are used.

Calibration has been an important aspect of research in augmented reality, as well as in other fields, including robotics and computer vision. Although well studied in computer vision community, camera calibration has found limited

use in augmented reality. Tuceryan *et al.* discuss the requirements for a video see-through system in [6]. Azuma and Bishop [1], and Janin *et al.* [4] describe techniques for calibrating a see-through head-mounted display. Recently, Kato and Billinghurst describe an interactive HMD calibration method [5] that uses multiple points on a grid. McGarrity and Tuceryan experimented with a dynamic through-the-lens method for HMD calibration [9]. Gottschalk and Hughes [3] present a method for auto-calibrating tracking equipment used in augmented and virtual reality. Holloway describes offline methods for finding sources of error in AR systems in [10].

More recently, Tuceryan and Navab [7] introduced a dynamic HMD calibration method in which the user aligns a series virtual crosshairs one-at-a-time over a point in the real scene. During the calibration, the user is free to move their head anywhere within the tracked workspace. After six or more such alignments, the method recovers a projection matrix that models the HMD-eye combination as a pinhole camera. Genc *et al.*, in [2] extended this method to the stereoscopic case where the fused virtual crosshairs are aligned with the scene point in 3D.

One of the most difficult problems associated with calibrating optical see-through HMDs is determining the accuracy of the system. Traditional image-based methods are of no use since we do not have access to the augmented image which is formed on the user's retina. Thus far, there have been two main approaches to accuracy verification for see-through displays. The first is to have the user calibrate the HMD and then report the qualitative accuracy of the alignment of a computer model to its real-world coun-

terpart, *i.e.*, “acceptable,” or “unacceptable.” The second method uses a camera to replace the human eye and conducts image-based measurements to assess the accuracy of the alignment. The former method is quick and easy, but it is subjective and gives no metric information which some applications may need. The latter method is performed by mounting a camera to the HMD so that it “sees” through the display panel. This is not very practical, nor does it guarantee that the measured accuracy will be observed by the user since a camera is only an approximation of the eye. Furthermore, the method is a very tedious process that must be performed offline since the camera is mounted where the user’s head would normally go.

We have developed a novel online method to measure the registration accuracy of an optical see-through HMD. Our initial description of the system can be found in [8]. This is the first such method to provide quantitative measurement as well as information on how to correct the current calibration of the optical see-through system. Our proposed method produces a repeatable, objective measurement of the error in an optical see-through system while it is running.

## 2. EVALUATING A CALIBRATION

Let us consider an augmented reality system with an optical see-through HMD and a real-time tracking system. Assuming that the user has calibrated the system along with the HMD, we can overlay graphics onto the real workspace with some unknown accuracy. Our aim is to measure the accuracy with which the 2D image is being generated on the HMD. The results from the system can be used in three different ways. First, we can provide accuracy information about a calibration. This information can be used to determine the expected registration accuracy at a given distance. For instance the system could report, “At 70 cm away from the target, the user can correctly identify items which are 1 cm apart.” This is useful in determining if the calibration is good enough for a particular application. Next, we can use the system to identify structured errors in the tracking system. For example, a magnetic tracker may produce structured errors in part of its radius due to a metal table. In this case we could use this to identify such problem areas.

### 2.1. Evaluation Module

We propose an evaluation module which is comprised of an optical see-through AR system and

a touch sensitive board. Figure 1 shows a schematic of the system. At any time after calibration, the user may invoke the evaluation module. First, the module superimposes a virtual object, *e.g.* a small sphere, onto a known position on the board.<sup>1</sup> Next, the user is asked to touch the board at the perceived location of the object. The module then moves the sphere to another location and the process repeats. Finally, after a sufficient number of points have been displayed and chosen, the module computes and displays the system errors. Note that since the system is running during the process, the user’s head is being tracked so they are free to move around during the validation process.

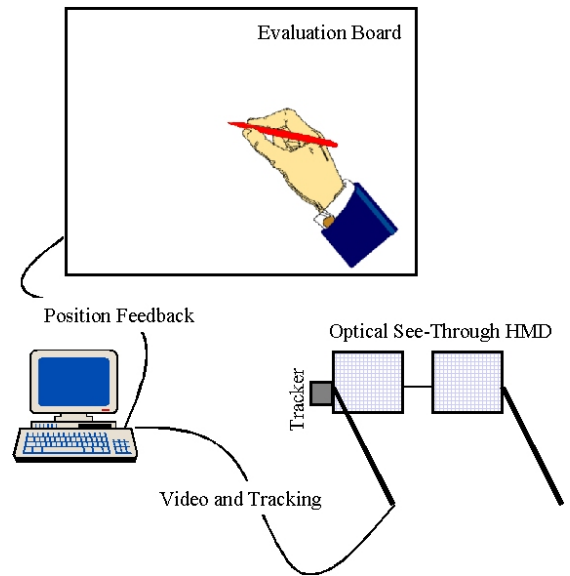


Figure 1: The optical see-through evaluation system.

### 2.2. Calibration Validation and Adjustment

For our error metric, we use the Euclidean distance between the projection,  $q_b$ , of the observed virtual point,  $q_w$ , onto the board and its true location,  $p$ . The geometry for this computation is shown in Figure 2. Given  $p$  and  $q_b$  we write the planar error as  $\|p - q_b\|$ . The individual distances between the virtual and real points can be plotted against one another to show the error field. We may also look at the average and maximum errors for absolute tolerance information. If the accuracy is insufficient, the user may be asked to adjust their calibration.

<sup>1</sup>This implies that the evaluation board must be calibrated into the system as well.

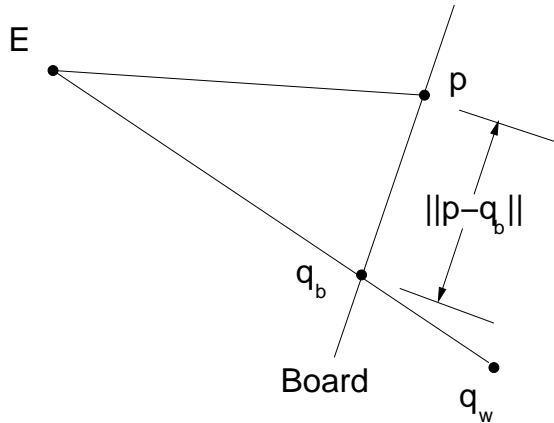


Figure 2: Error is measured in the plane of the evaluation board  $B$  as seen from the eyepoint  $E$ .

Another possible use of the results is in calibration adjustment. During a typical venture into an augmented environment, the user may accidentally move the HMD with respect to their eyes which could invalidate the calibration. In this situation we would like to re-validate the system. During this validation, we can use the collected data to adjust the user's previous calibration rather than re-calibrating the whole system. For instance, the adjustment can be made by re-projecting the observed points and running the SPAAM algorithm described in [7] using

$$\rho' p_i = \mathbf{\Pi}' \mathbf{T}' q_o, \quad (1)$$

as new observations, where the projection matrix  $\mathbf{\Pi}'$  and the transformation  $\mathbf{T}'$  represent the adjusted calibration and  $p_i$  is the image plane location of the observed point. The entire SPAAM system can then be re-solved to obtain the corrected projection matrix.

### 3. EXPERIMENTAL RESULTS

In this section, we present the results from two different AR systems. The first system uses a magnetic tracker and the second uses an infrared video-based tracker. Both systems have monocular displays which were calibrated with the same method. After calibration, the users invoked the evaluation module described in Section 2.1. The results for the systems are shown in Figures 3 and 4. In these plots, the + symbols represent the actual locations of the points provided by the validation modules and the × symbols show the observed locations. The circles provide visual feedback of the errors at each location.

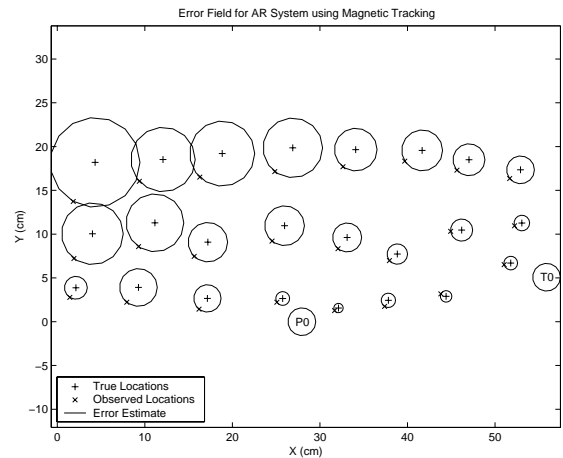


Figure 3: Error fields for an AR system which uses a magnetic tracking system.  $PO$  indicates the calibration origin and  $T0$  indicates the tracker origin.

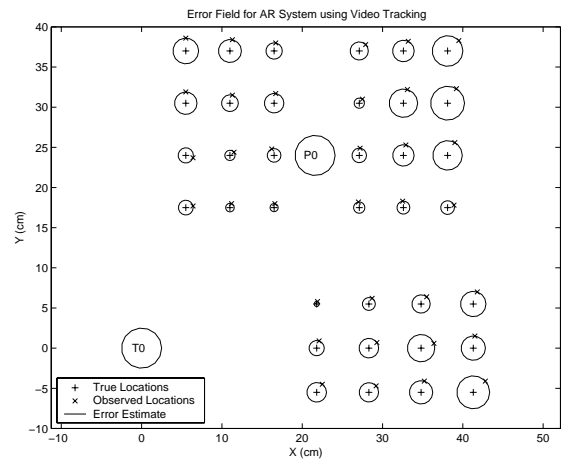


Figure 4: Error fields for an AR system which uses an infrared video tracking system.  $PO$  indicates the calibration origin and  $T0$  indicates the tracker origin.

#### 4. DISCUSSION

From Figures 3 and 4 we can see that perceived error tends to be proportional to the distance from the tracker. This indicates that tracker error accounts for a great deal of the overall error. It also indicates that the video-based tracker tended to have smaller errors overall. The video system had a slightly smaller work area, but that could be remedied by adding more fiducials to the scene.

#### 5. CONCLUSION

In this paper, we summarized a general method to objectively evaluate an optical see-through augmented reality system. Our method is very easy to use and produces quantitative measurement of the error in registration of the real and the virtual. This can be done while the user is still wearing the optical see-through head-mounted display. This system is capable of estimating the accuracy limits of an application and detecting structured errors in the tracking system. Additionally, the quantitative measurement can be used to automatically correct the calibration of the system to account for these errors.

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