LARGE SCALE CALIBRATION FOR AUGMENTED REALITY ON CONSTRUCTION SITES

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ABSTRACT: Accurate calibration methods are a key to achieve accurate registration in AR systems. Most calibrations developed thus far represent the system accuracy as pixel errors regardless of the view distance. Examination of work tasks in construction, however, indicates that the system accuracy may not satisfy the accuracy demands of specific work tasks due to variations in the view distance. This indicates the necessity of large scale calibration for construction sites for seeing objects at longer ranges with satisfactory system accuracy. This paper proposes a new scheme for large scale AR calibration for construction sites.

KEYWORDS: Augmented Reality, large scale calibration, construction

1. INTRODUCTION

Augmented Reality (AR) is one of the advanced computer-based technologies that can provide new visualization tools for the construction industry. Researchers have noted this opportunity for applying AR and have been seeking ways to exploit it in the construction industry for at least a decade. Several research studies in Architecture, Engineering and Construction (AEC) have demonstrated the potential of AR as a visualization aid for such applications as locating underground structures (Roberts et al. 2002), accessing architectural maintenance information (Webster et al. 1996; Kensek et al. 2000), architectural assembly guidance (Webster et al. 1996), infrastructure field tasks (Hammad et al. 2002), outdoor architectural designs (Thomas et al. 1999), urban planning (Shen et al. 2001), design detailing (Dunston et al. 2002), construction operation simulation (Behzadan and Kamat 2005), and post-disaster evaluation of building damage (El-Tawil and Kamat 2006). The AR systems developed in these studies are mostly still in the conceptual or early prototype stages.

There are still critical technical hurdles that must be addressed before AR can be embraced by the AEC industry. In order to develop compelling AR environments, enabling technologies for displays, tracking, registration, and calibration are needed. The registration problem continues to be one of the most basic challenges currently limiting AR applications, the crucial factor being the accurate and precise tracking of the user's viewing orientation and position. To make effective AR systems, it is necessary to develop accurate long-range sensors and trackers that report the locations of the user and objects in the environment. Accurate calibration methods for these tools are key to achieve accurate registration in AR systems. Even though some highly accurate tracker methodologies are available, inaccurate calibration can produce significant misalignment in registration. Many studies in AR have been done to explore compelling trackers and calibration methods.

To develop compelling trackers and calibration methods for AR systems for the construction site, the characteristics of the construction site should be considered. Construction sites tend to be expansive in nature which indicates that AR systems utilized as visual aids for the construction site need to cover a large range while maintaining high accuracy. While some small scale indoor AR systems achieve acceptably accurate registration, most of large scale AR systems developed so far still do not provide compelling registration. Most of the studies in large scale AR systems have focused on developing accurate large scale trackers (You et al., 1999; Behringer, 1999; Azuma et al., 1999; Thomas et al., 2000; Ribo et al. 2002; Jiang et al. 2004) but they have not considered how to ensure required system accuracy as it is influenced by the view distance.

2. SPATIAL ASPECTS OF CONSTRUCTION SITES

As sated above, construction sites can generally be characterized as expansive. Project participants perform work tasks within that space according to the project design. Starting with tasks outlined by Everett (1991), Shin (2007) presented work tasks in industrial construction and potential AR-based solutions to improve task performance. Tables 1 and 2 show the work tasks and possible useful AR solutions for them. Since the accuracy of AR systems may depend on distance, understanding how the AR solutions work from spatial aspects of construction sites reveals how the AR systems for construction must be calibrated.

Table 1: Physical work tasks and AR solutions (Shin 2007)

Work Task	Definition	AR Solutions
Layout	Determining, ascertaining, and marking dimensions	Virtual reference points indicating target measuring points
Excavation	Breaking up, turning over, removing, or filling soil	A 3D design of a target area and desired excavation depth
Penetrating	Making a hole in the ground by boring or driving	No benefits from AR
Conveying	Moving heavy material to deposit it at a destination	No benefits from AR
Cutting	Penetrating or separating into parts with a sharp edge instrument	No benefits from AR
Positioning	Moving heavy objects to certain locations and orientations for installation	A 3D configuration of an element
Placing	Moving light or medium weight objects to certain locations for installation	No benefits from AR
Connecting	Attaching, fastening, joining components	No benefits from AR
Spreading	Distributing a paste or liquid material over an area or in a volume	No benefits from AR
Finishing	Applying mechanical treatment for a desired or particular surface texture	No benefits from AR
Spraying	Dispersing a liquid or particles in a mass or jet of droplets from a predetermined distance from the surface	No benefits from AR
Covering	Overlaying or spreading sheet material over a surface	No benefits from AR
Inspection	Examining installed workmanship by an approved state or city personnel to verity quality and that the work is installed to the pre-approved drawings and that the work meets all codes	A 3D configuration of a critical element

Table 2: Informational work tasks and AR solutions (Shin 2007)

Work Task	Definition	AR Solutions
Coordination	Making sure that all trades work will fit in a predetermined area as per engineer drawings.	Digital photo scenes of work areas with 3D designs
Supervision	Seeing if work is performed as planned.	A 3D design of a desired observing area
Commenting	Conveying supplementary information regarding a task.	A 3D design of a desired instructing area
Strategizing	Figuring out the detailed procedures for specific tasks.	A virtual drawing for the spatial organization of elements

3. SUMMARY OF CALIBRATION METHODS

The registration problem is one of the most basic problems currently limiting AR applications (Azuma 1997). Generally, extensive camera calibration is needed to achieve accurate registration in AR systems. There are numerous studies of calibration methods for AR.

Some studies present calibration methods for video-based AR systems (Tuceryan et al. 1995; Bajura and Neumann 1995; Grimson et al. 1996; Kutulakoos and Vallino 1998; Berger et al. 1999; Li et al. 2000; Rueckert and Maurer 2002). Tuceryan et al. (1995) described calibration requirements and procedures for a monitor-based AR system. Their calibration method was based on the non-coplanar algorithm. Bajura and Neumann (1995) proposed a dynamic registration correction approach for video-based AR systems. Their approach initially calibrates camera parameters based on the coplanar algorithm and then the camera orientation parameters are dynamically adjusted to correct image registration error on a frame-by-frame basis. This closed-loop method for correcting registration error is based on the detection of red LEDs placed in the environment. Grimson et al. (1996) presented an automatic registration method, which is based on vision techniques, for medical data superimposed onto a patient in a video-based AR system. In their method, the camera calibration parameters are automatically updated in real time based on fiducial points on a patient. Kutulakoos and Vallino (1998) proposed a calibration-free AR system that is video-based. Their system does not use any metric information about the camera calibration parameters or the 3D locations and dimensions of the environment's objects. Their system only requires the ability to track across frames at least four fiducial points that are specified by the user during system initialization. Berger et al. (1999) compared two kinds of camera calibration algorithms (coplanar and non-coplanar). Their study indicates that the non-coplanar algorithm is much more accurate than the coplanar algorithm. Li et al. (2000) proposed a closed-form calibration solution, followed by a nonlinear refinement based on the maximum likelihood criterion. Rueckert and Maurer (2002) proposed an intensity-based calibration algorithm that determines camera calibration parameters by maximizing the similarity between a virtual view of the calibration phantom and the real view of the calibration phantom.

There are also several studies of calibration methods for optically based AR systems (Janin et al. 1993; McGarrity and Tuceryan 1999; Kato and Billinghurst 1999; Tuceryan et al. 2002; Hua et al. 2007). The optically based AR systems have more challenges for calibration than the video-based AR systems because the optically based AR systems do not support direct access to the image data to be used in various calibration procedures (Tuceryan et al. 2002). Janin et al. (1993) presented an interactive calibration approach for an optical see-through head-mounted display (HMD), which uses a calibration object with multiple points. Their approach is based on nonlinear methods. McGarrity and Tuceryan (1999) proposed an interactive calibration approach for an optical see-through HMD, which requires the simultaneous alignment of multipoint configurations for calibration. Their approach is similar to the approach of Janin et al. (1993), but they use a projection matrix representation to model the camera which can be estimated by linear methods. Kato and Billinghurst (1999) proposed an interactive camera calibration method based on vision techniques for an optical see-through HMD, which uses multiple points on a grid. Tuceryan et al. (2002) presented an interactive calibration approach for an optical see-through HMD, which uses only a single point in the world for calibration. Hua et al. (2007) proposed a systematic calibration method for a head-mounted projective display (HMPD). Their calibration method accurately models the projection process in an HMPD system with a viewing device that takes into account practical misalignment in the HMPD system.

4. DEFINING OPERATIONAL SPACES

A structured framework is helpful to classify calibration methods for construction work tasks. The authors consider one view that specifies operation spaces in terms of the distance between the target object and the required accuracy. The distance attribute is either of *short, medium* or *long* while the required accuracy attribute is either of *high, intermediate* or *low*. Figure 1 shows the authors' rationalization of operational spaces for the work tasks from Shin (2007).

Distance / Required Accuracy	*Short*	*Medium*	*Long*
High	Layout, inspection, and positioning	Layout, inspection, and positioning	
Intermediate		Excavation and coordination	
Low		Supervision, commenting, and strategizing	Supervision, commenting, and strategizing

FIG. 1: Operational spaces for work tasks

Layout, inspection and positioning are generally performed based on detailed and accurate position and orientation of target objects. These work tasks are associated with handling target objects within near reach in a relatively close distance, so they require a *short* distance application of the AR system. Layout, inspection and positioning are also based on *medium* distance tasks when target objects are large. For example, a surveyor usually inspects a column from the ground. It will be a medium distance task to check the top of a column from a position on the ground and a highly accurate measurement is still necessary. Supervision, commenting and strategizing are generally performed based on a large picture of an associated work area, thus requiring a *medium or long* distance AR system. Some mismatch between virtual drawings and a real world scene does not much affect these processes, so a *low* accuracy is acceptable for these work tasks. Excavation has some margin of error but still requires accuracy somewhat. An operator of excavation equipment who is in the cabin and located a bit away from the ground needs a large view of an associated work area to safely drive equipment. A *medium* distance AR system with an intermediate accuracy is appropriate to these features of excavation. Coordination is generally performed based on somewhat large pictures of an associated work area, thus requiring a *medium* distance AR system. For coordination, some margin of error is acceptable but accuracy is still required somewhat. Thus, an *intermediate* accuracy is appropriate for coordination. Figure 1 illustrates that AR systems for construction sites need to be applied for various distances and accuracies.

System accuracy for video-based systems can be represented by the area in the object space covered by a single pixel. Then system accuracy is proportional to the distance between the camera projection center and the point to be measured. If the distance between the camera center and the point to be measured is fixed, then the system accuracy can be represented by a single number and should be equal to or less than the required task accuracy. A shaded area in Figure 1 indicates work tasks for which most AR systems, as found among various documented research prototypes, work fine with respect to the system accuracy, while the unshaded area indicates work tasks that require a higher accuracy than the typical AR system accuracy. The main object of this paper is to suggest a calibration method for the work tasks in the unshaded area of Figure 1. This calibration method is referred to as "large scale calibration" in the sense of seeing the objects in a large space. From Figure 1, it is found that some layout, inspection, and positioning require a large scale calibration. Most studies in calibration have been limited to system accuracy without considering a significant range of changes in view distance. Therefore, the question comes up as to what issues must be addressed to achieve a large scale calibration.

5. CALIBRATION SOPHISTICATION

This paper focuses on video-based AR systems that use a pinhole CCD (charge-coupled device) camera. Figure 2 describes the imaging geometry of a pinhole camera. Based on the assumption that the AR camera is perfectly calibrated, when a target point (X) is measured at the view distance (D) with the camera having focal length (f), a single image pixel size (v) in the CCD array covers size d in the object space. If the AR system measures the target point (X) with the required accuracy (σ), the size in the object space (d) which is covered by one pixel should be equal to or less than the required accuracy. The view distance that can provide the required accuracy can be calculated as follows:

$$f : D = v : d$$

For the system accuracy that satisfies the required accuracy,

$$d = \frac{D \cdot v}{f} \leq \sigma$$

Thus, $D \leq \frac{f \cdot \sigma}{v} \leq D_{\max}$, where D_{max} is the maximum view distance that can provide the required accuracy for that focal length.

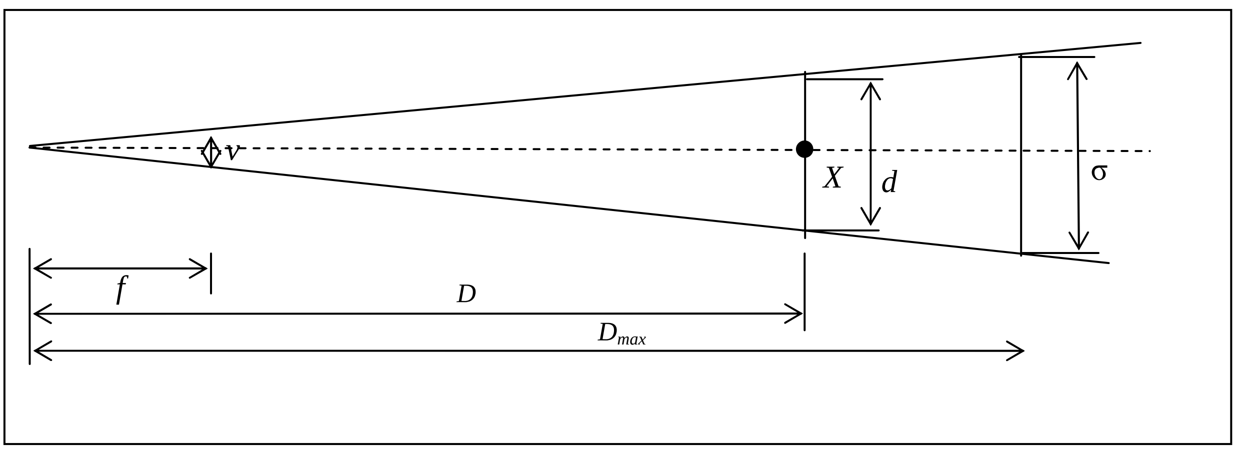

FIG. 2: Imaging geometry of a pinhole camera.

As shown in Figure 2, however, if the view distance is larger than D_{max}, any points in the object space covered by a pixel will be imaged on the pixel even though the points are beyond the required accuracy. That is, the target point beyond the required accuracy can be shown as if it is within the required accuracy, if the view distance is longer than D_{max}.

There are several ways to overcome this problem. One of the easiest ways is just to constrain the view distance to be less than or equal to D_{max}. However, this constraint makes an AR system very inefficient because it requires users to perform work only within D_{max}, thus compromising AR system usability. Another approach might be to change the pixel size (v). Since the CCD array size is fixed, it is very hard to change CCD array size dynamically according to the view distance. Changing focal length (f) instead of changing other parameters can be a solution. This solution is the most practical approach in terms of the usability and techniques to be applied.

By adjusting focal length (f), intrinsic parameters and lens distortions change. Fraser and Al-Ajlouni (2006) developed a zoom-dependent camera calibration method for close-range photogrammetry. Their approach also can be applied to calibrate video-based AR systems that require various focal lengths.

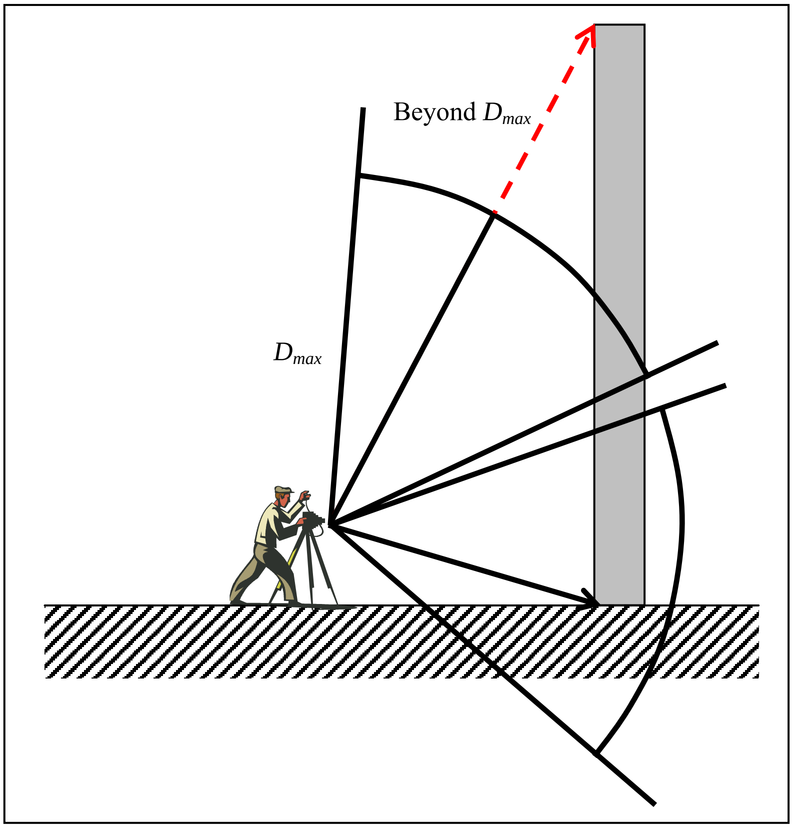

FIG. 3: Beyond the maximum view distance

Once the AR system is calibrated, the view distance that can be measured with the required accuracy should be delivered to the users efficiently. If not, users cannot decide whether the target point is within the required accuracy. For example, a user inspecting a column with an AR system which compares the actual column position and orientation to the designed column position and orientation can have the problem depicted in Figure 3. The user can check the position of the bottom of the column with the required accuracy, but cannot do so for the top of the column. In this case, some indications such as different colored virtual indicator lines should be provided to inform the user, so that the user can change the focal length (that is, zoom in) to check the top of the column with the required accuracy.

This solution to the camera calibration challenge for large scale applications is a critical step toward establishing the feasibility of AR applications for construction sites. The selection of the most promising registration approach will be the next critical step.

6. CONCLUSIONS

This brief treatment of the large scale AR calibration for construction sites has yielded the following conclusions:

- The AR system accuracy is dependent on the view distance, so the view distance must be considered in the AR calibration to satisfy the required accuracy for specific work tasks.
- The most practical approach to the distance-dependent system accuracy is to change the focal length of the camera lens. The large scale calibration approach which uses the zoom-dependent calibration method can provide the AR calibration corresponding to the changing focal length.

The next steps of research on this topic will involve developing an AR system with large scale calibration that is based on the zoom-dependent camera calibration method of Fraser and Al-Ajlouni (2006).

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