CAMERA CONSTRAINT ON MULTI-RANGE CALIBRATION OF AUGMENTED REALITY SYSTEMS FOR CONSTRUCTION SITES

SUBMITTED: January 2008
REVISED: May 2008
PUBLISHED: October 2008
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ABSTRACT: *Accurate calibration methods are critical to achieving accurate registration in Augmented Reality (AR) systems. Most calibration methods developed so far focus on achieving the accurate registration within certain view distance ranges. Examination of work tasks in construction, however, indicates that the AR system registration accuracy may not satisfy the accuracy demands of work tasks due to variations in the view distances. This fact indicates the necessity of multi-range calibration for measuring the positions of objects at various view distances with appropriate accuracy. This paper is an initial investigation of the constraints associated with construction sites conducted to ensure the appropriate system accuracy of multi-range AR systems designed for use in these environments.*

KEYWORDS: *Augmented Reality, multi-range calibration, construction, view distance*

1. INTRODUCTION

For at least a decade, Augmented Reality (AR) has been drawing the interests of researchers in Architecture, Engineering, and Construction (AEC) because of its potential as a visualization aid in AEC (Webster et al. 1996; Kensek et al. 2000; Shen et al. 2001; Roberts et al. 2002; Hammad et al. 2002; Dunston et al. 2002; Behzadan and Kamat 2005; El-Tawil and Kamat 2006). However, there are still numerous 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 prohibiting implementation of 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 (e.g. Foxlin et al. 1998; Welch et al. 2001; Wormell et al. 2007) and calibration methods (e.g. Li et al. 2000; Rueckert and Maurer 2002; Hua et al. 2007).

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 multiple view distance ranges while maintaining appropriate accuracy. While some small scale indoor AR systems achieve acceptably accurate registration, most of the large scale AR systems developed so far still do not provide compelling registration of high accuracy. 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) to achieve accurate registration of virtual objects on the real world scene by removing tracking errors. Even if a tracking algorithm is perfected, there is yet another error resource affecting registration, the calibration methodology. The compelling registration of a virtual object on the real world scene in AR will be achieved by removing calibration errors as well as tracking errors.

Still, yet another factor other than these registration accuracy determinants must be considered for AR systems designed for construction tasks requiring certain accuracies, the coverage area of a real object by a point (pixel) of the virtual image aligned to it. From our experience with a previous study (Shin 2007) with our AR prototype system for inspection, ARCam, it was recognized that the benefit of AR systems for tasks in construction can be affected by the coverage of real object by a point of the virtual image. If the coverage is too large to allow the AR system to meet accuracy (and precision) requirements for a specific task in construction, the AR system would not be much of a useful visual aid technology for the task even though the registration of virtual object to the real world scene is perfect. Fig. 1 and Fig. 2 conceptually illustrate this issue with ARCam that is applied to inspecting the plumbness of a steel column. In Fig. 1, the virtual line (dark red) on the left edge of the column (blue) and the 1.5 mm gap (white slot between the purple strip and column) are clearly identified. In this view, ARCam with a short view distance has at least 1.5-mm precision. Meanwhile, in Fig. 2, it is not clear whether the virtual line is on the left edge of the column or on the 1.5-mm gap. This indicates that ARCAm with the long view distance as it currently functions, cannot deliver 1.5-mm or higher precision. In this paper, the required coverage for a specific task is defined as the *system accuracy*.

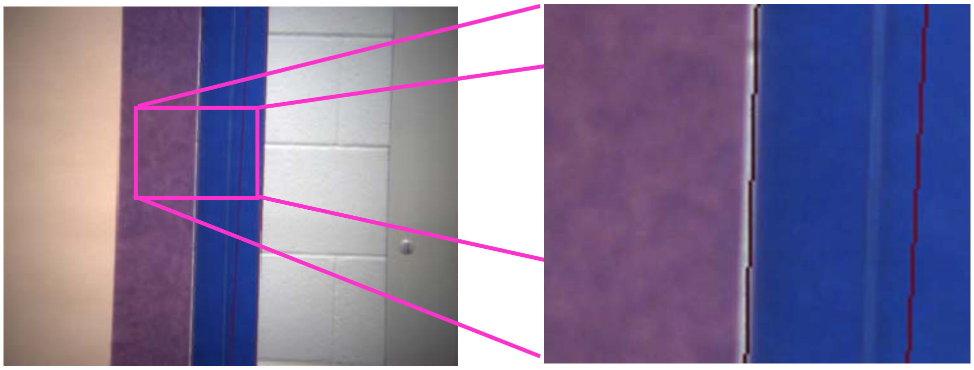

FIG. 1: Conceptual demonstration of virtual line and 1.5 mm real gap at a short view distance with ARCam

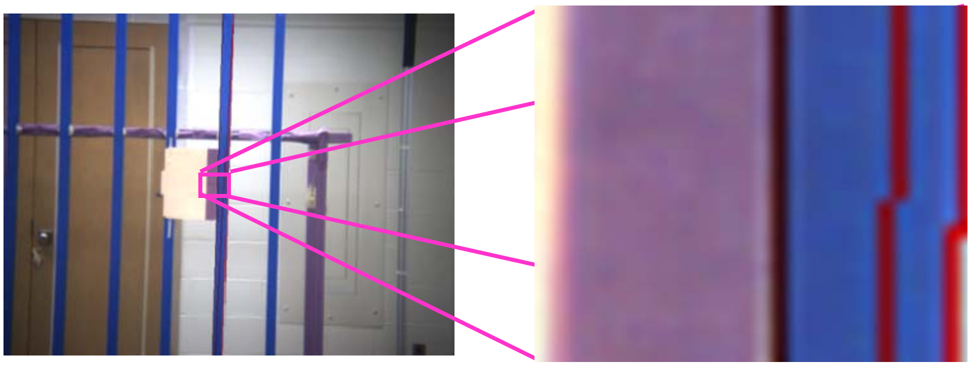

FIG. 2: Conceptual demonstration of virtual line and 1.5 mm real gap at a long view distance with ARCam

On a construction site, the view distance between the target object and the AR system would be varied depending on the types of tasks. As the view distance increases, the coverage of the real object by a point of the virtual image gets larger and the AR system may not provide the system accuracy for a specific task as shown in Fig. 2. To avoid this problem, a closer view (as shown in Fig. 1) that decreases the coverage may be necessary. This situation being characteristic of a construction site indicates the necessity of systems with a multi-range view to meet the system accuracy requirement regardless of the viewing distance. The multi-range view requires multi-range calibration. The main objective of this paper is to investigate the camera (pixel size) constraint on multi-range calibration, which satisfies the system accuracy for video-based AR systems on construction sites. Through defining the constraint, the specification of a camera for video-based AR can be determined to fulfil the varied view distance requirements.

2. SUMMARY OF CALIBRATION METHODS

As demonstrated above, 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 optically based AR systems. 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 which is needed for 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.

There are also several studies of calibration methods for video-based AR systems. For example, 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 the 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.

Most of these studies focused on single-range calibration. As shown above, AR systems for construction tasks require multi-range calibration. Due to the lack of studies of multi-range calibration, the camera constraint on multi-calibration for video-based AR also has not been addressed. As mentioned above, the successful adoption of AR in construction requires not only the accurate registration but also the satisfaction of the system accuracy for a specific task.

3. SPATIAL ASPECTS OF CONSTRUCTION SITES

Construction sites can generally be characterized as expansive, presenting a wide range and variety of spaces through or over which site personnel must navigate. Project participants perform work tasks within that overall space according to the project design. Starting with tasks outlined by Everett (1991) to conduct a task-technology fit exercise, Shin (2007) presented work tasks common 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. In order to use the AR systems in the work tasks effectively, the accuracy of AR systems has to satisfy the required accuracies of the various work tasks. To achieve this, the constraint on the AR system according to the view distance must be identified. The identification of the constraint can be done by comparing the required accuracy of the work tasks and the accuracy of AR systems as they vary with the view distance. The required accuracy of the work tasks can be found or extrapolated from specifications or standards. The view distance affecting the accuracy of an AR system can be revealed by understanding how the AR solutions work from spatial aspects of construction sites.

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	The virtual 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	The virtual 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

Table 2: Physical work tasks and AR solutions (continued)

Spraying	Dispersing a liquid or particles in a mass or jet of droplets from a predetermined distance from the surface	No benefits from AR
Work Task	Definition	AR Solutions

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	The 3D configuration of a critical element

Table 3: Informational work tasks and AR solutions (Shin 2007)

Work Task	Definition	AR Solutions
Coordination	Organizing and determining upcoming work flows or resource allocation	The viewpoint changeable 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

4. DEFINING OPERATIONAL SPACES

The authors consider one view that specifies operational spaces, which are theoretical domains which are defined by distinct characterizations of functional needs for negotiating a physical space and the correspondingly available navigational references (Dunston et al. 2007). Here the operational spaces are defined explicitly in terms of the view distance and the required accuracy of work tasks. The operational spaces may be defined through a structured framework which is helpful to relate the view distance affecting the accuracy of AR systems and the required accuracy of the work tasks. Based on the structured framework, the constraint on multi-range calibration for AR systems can be systematically identified. In defining operational spaces, only the work tasks found by Shin (2007) to be significantly benefitted by AR (layout, excavation, positioning, inspection, coordination, supervision, commenting, and strategizing) have been included.

4.1 Required Accuracy Standards

The required accuracy of the work tasks are noted from specifications and standards of common practice in addition to practical aspects of the task itself. Because layout is the basis of the location and orientation of a building, i.e., the starting point for the building, the result of layout is considered the most accurate and assumed to be without errors. Thus, the required accuracy for layout is 0 mm. However, when a control point is marked with a marking tool such as marker pen, spray, nail, etc., the control point is overlapped by the diameter (or thickness) of the marking tool. In the assumption that the diameter (or thickness) of such marking tools is about 1 mm, the practical required accuracy for layout may range from approximately 0 mm-1 mm.

One of the most critical and high-accuracy-required elements with regard to positioning in industrial construction is the structural column. It was noted that the erection tolerance for steel columns is stricter than the one for concrete columns from reviewing the AISC code (2005) and the ACI code (2005). Thus, the erection tolerance for steel columns is used in this paper to define the relationship between the required accuracy and the work distance for positioning. Position tolerance for anchor bolts for steel columns is 6 mm. Plumbness tolerance of steel columns is 1/500 of the distance between working points (the actual center of the member at each end of the shipping piece), but also must be not more than 25 mm or 50 mm from the established column line, depending on its location, in the first

20 stories. Above this level, its plumbness tolerance is 1/16 in. (1.6 mm) per story, but also must be not more than 50 mm or 75 mm from the established column line, depending on its location. In the 36th story, the plumbness tolerance becomes 50 mm or 75 mm from the established column line. Beyond this story, the plumbness tolerance stays constant at 50 mm or 75 mm.

The required accuracy for excavation is noted from elevation tolerances. In excavation, elevation tolerance is 13 mm for grading inside building lines, 25 mm for grading lawn and unpaved areas, 25 mm for grading walks, and 13 mm for grading pavements (Office of Construction & Facilities Management 2004).

Inspection in industrial construction needs to cover earthwork and elements or structures in a plant built. For the required accuracy for inspection, the tolerances for positioning and excavation above are applied in the same manner.

The required accuracies for coordination, supervision, commenting, and strategizing are not yet defined statically. These work tasks, however, would not use AR aids for absolute references for installation but might use them for understanding a design in the context of a real construction site (Shin 2007). Therefore, some mismatch between virtual drawings and a real world scene does not much affect these processes.

4.2 View Distance Ranges

The view distance associated with the work task can be found mainly based on understanding how the AR solutions work from spatial aspects of construction sites.

AR may enable workers to perform layout within near reach in a relatively close distance (Shin 2007), by marking according to a virtual layout superimposed onto a real site. An individual might walk the site with a "see-through" device that would display critical layout points. Maximum reach range is approximately 0.5 m as calculated from the arm length of a 95th percentile male (Proctor and Zandt 1994). Thus, the work distance for layout may range approximately 0 m-0.5 m.

Positioning may also include a near reach work distance as well. In positioning steel columns, the work distance may be extended to 12 m, considering that a typical height of a shipped steel column piece is 12 m (Peurifoy and Oberlender 2002). Thus, the work distance for positioning steel columns may range approximately 0 m-12 m.

The work distance for excavation may be defined as the distance between the operator's view point and the end of the tool (blade or bucket) of the equipment. The work distance for excavation is noted to range approximately 3 m-18 m as derived from the dimensions of excavation equipment such as backhoes, wheel loaders, dozers, motor graders, and scrapers (Caterpillar 2007).

The work distance for inspection with AR may be inferred from the work distance for conventional inspection using surveying instruments. Shorter work distances for inspection would require more movements of surveyors or inspectors and more frequent setup of the inspection instrument. Thus, to sustain the usability of AR in inspection, the work distance for inspection with AR should not be less than the work distance for conventional inspection. In this paper, the work distance for inspection with AR is defined to be the same as the work distance for conventional inspection. The work distance for inspecting steel columns is at least the height of a steel column. As a building rises in height, the work distance for inspecting steel columns increases up to more than the building height. The work distance for conventional inspection of excavation is practically no longer than about 50 m-60 m, because it is hard to accurately obtain elevations on the elevation rod from the inspection device such as a level when the distance from instrument to rod is more than about 50 m-60 m. Thus, the work distance for inspecting excavation may range up to 60 m.

Coordination, supervision, commenting and strategizing are generally performed based on a large picture of an associated work area. Thus, the work distances for these work tasks may be a bit away from a work area or even may be quite away from the target object to have a picture of a work area in the context of a larger project view.

4.3 Matrix of Operational Spaces for Work Tasks

By combining the required accuracies and the work distances as noted above, the matrix of operational spaces for work tasks can be created. In order to make this combination easily, the required accuracy according to the work distance for each work task was specified to obtain the greatest required accuracy. For example, the required accuracy for excavation was simplified to be constant at 13 mm, even though there is only a 25-mm required accuracy in some cases. The required accuracy standards for inspecting steel columns was simplified to correspond to the work distance ranges between 0 m and 12.5 m (0 mm to 25 mm, linearly), between 60 m and 108 m (25 mm to 50 mm, linearly), between 12.5 m and 60 m (25 mm, constant) and beyond 108 m (50 mm, constant).

From the simplified relationship of the required accuracy and the work distance, the required accuracy attribute may be segmented into very high (0 mm-1 mm), high (1 mm-6 mm), intermediate (6 mm-13 mm), low (13 mm-25 mm), very low (25 mm-50 mm), and extremely low (50 mm-). From the description of the work distance above, the work distance may be segmented into near (0 m-0.5 m), very short (0.5 m-3 m), short (3 m-6.5 m), medium (6.5 m-18 m), long (18 m-60 m), very long (60 m-108 m), and extremely long (108 m-).

Under the required accuracy attribute, 1 mm is noted from the practically required accuracy for layout. 1 mm is also the required accuracy for inspecting or positioning steel columns within the 0.5-m work distance. 6-mm required accuracy is noted from inspecting or positioning steel columns within a 3-m work distance. 13-mm required accuracy is noted from excavation with the work distance of 3 m to 18 m. 13-mm required accuracy also corresponds to a 6.5-m work distance for positioning and inspecting steel columns. 25 mm is noted from the maximum required accuracy for inspecting steel columns within the 60-m work distance that is noted from the first 20 stories. 50 mm is noted from the maximum required accuracy for inspecting steel columns beyond a 108-m work distance that is noted from the first 36 stories. From the assumption that the height of a story is 3 m, the heights of the first 20 stories and 36 stories comes to about 60 m and 108 m, respectively.

Based on the required accuracy attribute and the work distance attribute, the matrix of operational spaces for work tasks (Fig. 3) was created. While making the matrix, inspections for steel columns and excavation were treated in a manner to obtain the greatest required accuracy in a given work distance range. For example, in the work distance up to 6.5 m, inspection for steel columns requires a higher required accuracy while inspection for excavation requires a higher accuracy in the work distance between 6 m and 60 m. Thus, the required accuracy for inspection for the work distance of 0-6.5 m is from inspecting steel columns and that for the work distance of 6.5 m-60 m is from inspecting excavation.

This operational space matrix clarifies the relationships between working sight (view) distances and accuracy standards for various tasks to which AR technologies might be applied. With these relationships established, the relevant parameters of viewing equipment, namely cameras used for video-based AR may be discussed.

View Distance (m) Required Accuracy (mm)	Reachable (0-0.5)	Very short (0.5-3)	Short (3-6)	Medium (6-18)	Long (18-60)	Very Long (60-108)	Extremely long (+108)
Ultimate (0-1)	Layout, positioning, and inspection						
High (1-6)		Positioning and inspection					
Intermediate (6-13)			Positioning, excavation, and inspection	Excavation and inspection	Inspection		
Low (13-25)				Positioning			
Very low (25-50)				Coordination, supervision, commenting, and strategizing	Coordination, supervision, commenting, and strategizing	Inspection, coordination, supervision, commenting, and strategizing	Inspection
Extremely low (+50)				Coordination, supervision, commenting, and strategizing	Coordination, supervision, commenting, and strategizing	Coordination, supervision, commenting, and strategizing	Coordination, supervision, commenting, and strategizing

FIG. 3: Matrix of Operational spaces for work tasks

5. DERIVATION OF THE CONSTRAINT

This paper assumes the use of video-based AR systems that use a pinhole CCD (charge-coupled device) camera. 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. The main objective of this paper is to investigate the camera constraint on multi-range calibration for AR systems on construction sites. Based on the matrix of operational spaces for work tasks, the camera constraint on AR systems can be suggested.

Fig. 4 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:

$$\frac{f}{D}=\frac{v}{d}$$

For the system accuracy that satisfies the required accuracy, the constraint equation is derived as follows:

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

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.

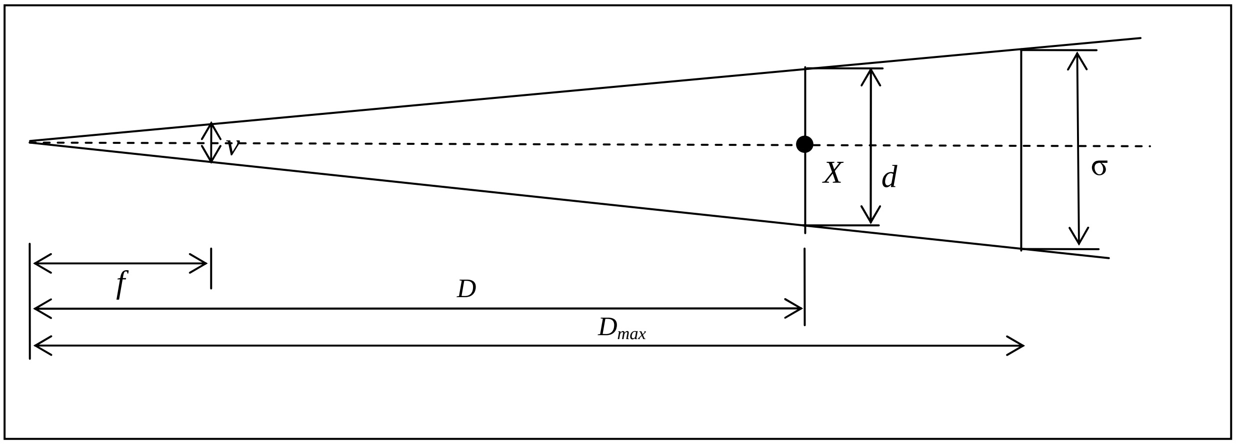

FIG. 4: Imaging geometry of a pinhole camera.

As shown in Fig. 4, 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 three ways to address 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. In the case of adjusting focal length (f), the range of the focal length should guarantee the required accuracy of given work tasks. To have an exact focal length range, the other three parameters (D, v, and σ) should be given. Since the pixel size of an AR system is different from one camera to another, it is more reasonable to leave the pixel size as a variable than to fix it as a constant. By introducing a focal length to pixel size ratio (f/v), the acceptable focal length range of any AR system can be represented. From the previous equation, the focal length to pixel size ratio (f/v) can be expressed by the constraint, $\frac{D}{\sigma} \le \frac{f}{v}$. Then the minimum focal length to pixel ratio is equal to D/σ . From the work tasks listed in Fig. 3, the minimum focal length to pixel ratios are determined and shown in Fig. 5 and Fig. 6. For example, to build a video-based AR system for inspection, the minimum focal length to pixel size ratio of an AR system is approximately 4,600. Because this ratio is the largest one through those for all the work tasks, the AR system satisfying this ratio will work for the other tasks. The minimum focal length to pixel ratio is important in the sense of accuracy assurance. In the designing stage of an AR system, users can efficiently build an AR system by choosing a camera system having a larger focal length to pixel size ratio than the minimums estimated by the required accuracies and working distances of expected work tasks.

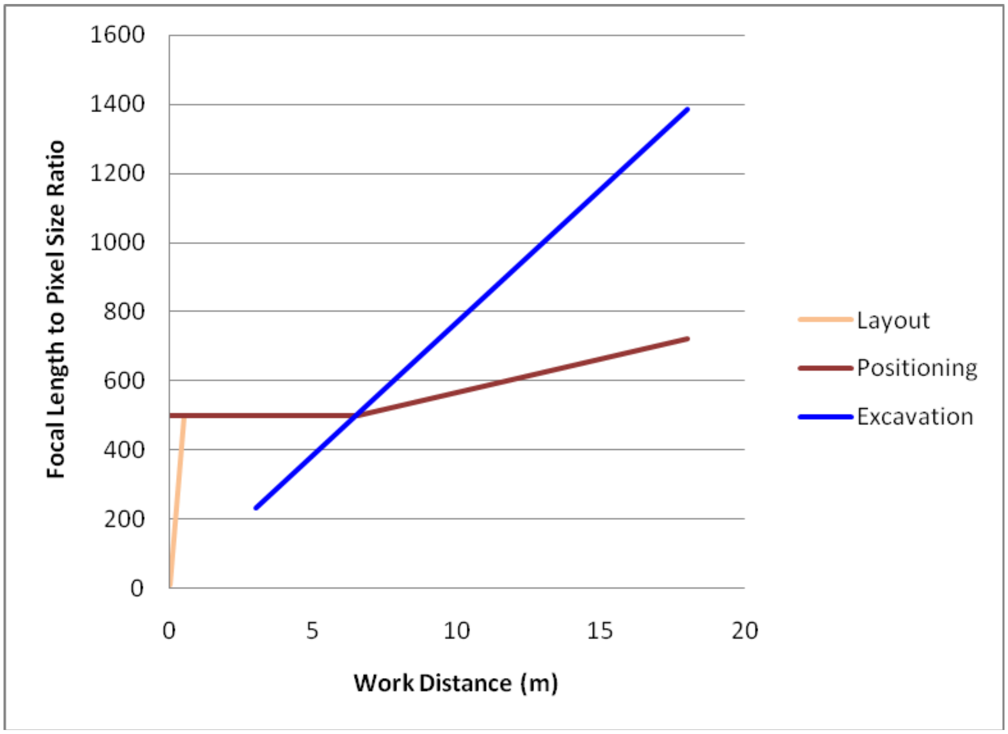

FIG. 5: Minimum focal length to pixel size ratio corresponding to work distances for layout, positioning, and excavation

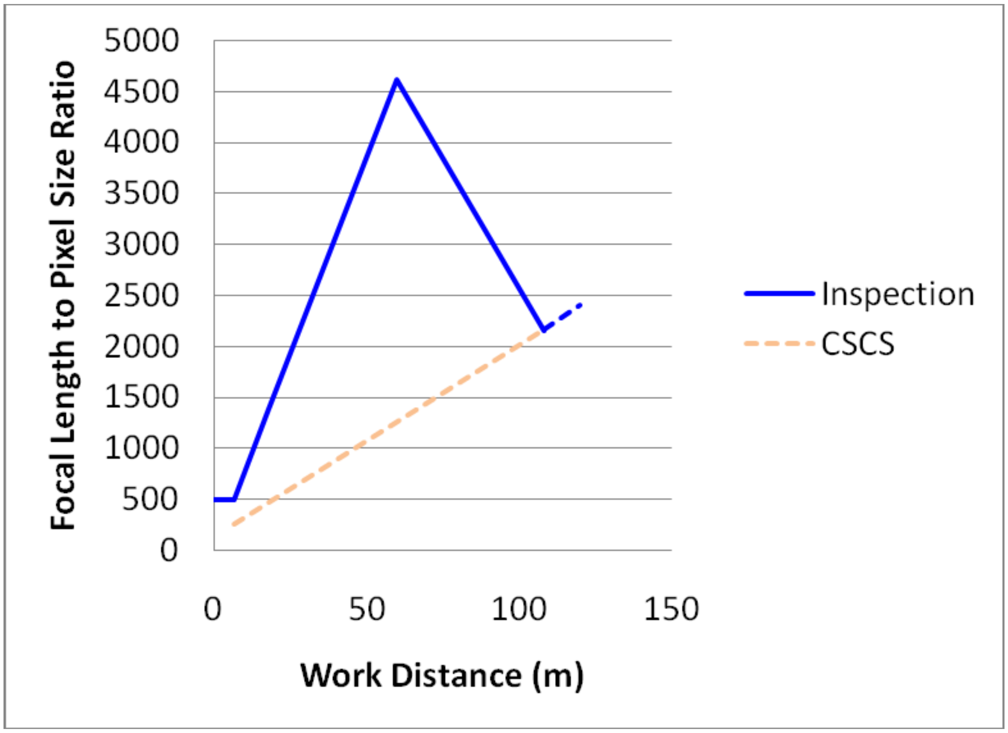

FIG. 6: Minimum focal length to pixel size ratio corresponding to work distances for inspection, coordination, supervision, commenting, and strategizing

In practice, the view distance plays an important role. Once a user selects an appropriate focal length for some work tasks, the required accuracy should be delivered efficiently over the view distance. If not, the user 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 Fig. 7. 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 alert the user to the need to change the focal length (that is, zoom in) to check the top of the column with the required accuracy.

Resolving the camera constraint on AR systems for construction sites 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. In addition to this, stereo imaging should be considered to better ensure meeting required accuracy by access to depth information.

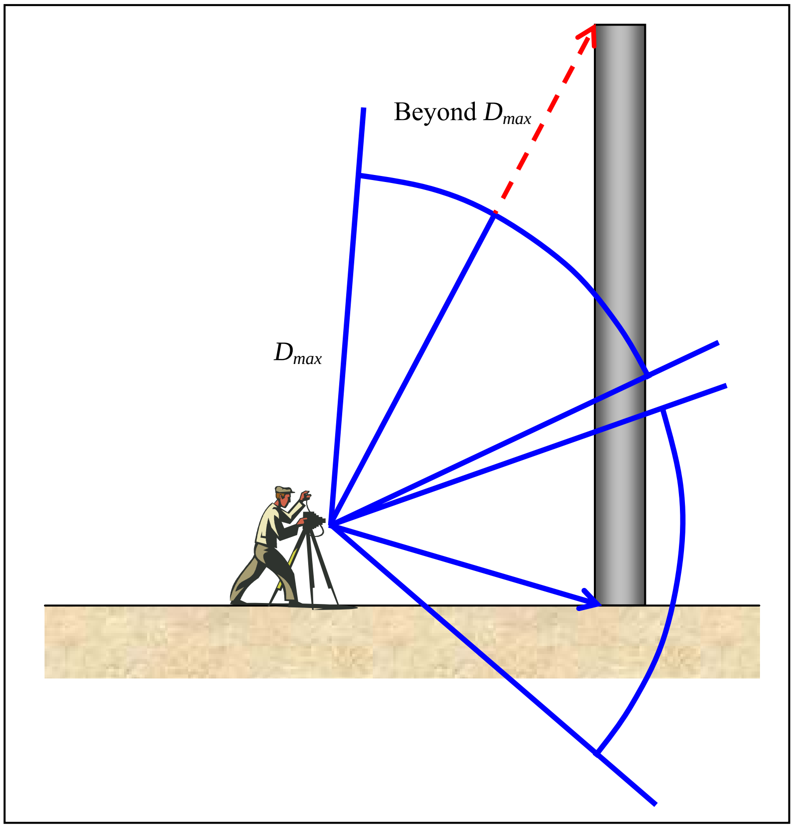

FIG. 7: Beyond the maximum view distance

6. CONCLUSIONS

The studies of AR systems have focused on the development of advanced tracking and calibration to achieve the compelling registration of virtual objects onto the real world scene. However, AR systems for work tasks in construction require appropriate system accuracy in terms of the coverage of a real object by a point of a virtual image other than the registration. The system accuracy of video-based AR systems is dependent on the view distance, so the view distance must be considered to ensure the AR system can satisfy the required accuracy for the work tasks. This study defines operational spaces in terms of the required accuracy of the work tasks and the view distance associated with them in a structured framework. Through the framework, the camera constraint on multi-range calibration for AR systems on construction sites can be systematically identified. Three methods are identified to achieve the appropriate constraint $\left(D \cdot v / f \leq \sigma\right)$. The authors decided that the most practical approach to the constraint challenge is to change the focal length of the camera lens. The derived focal length to pixel size ratio from the constraint is proposed for specifying the camera for an AR system. With the camera constraint, system accuracy in terms of the coverage of a real object by a point of the virtual image can be assured. The constraint also can provide a guideline to select an appropriate video camera for an AR system for a specific task. The proposed constraint in this study is limited to monoscopic imaging. To better ensure meeting required accuracy by access to depth information, stereo imaging should be considered.

Resolving the camera constraint on AR systems for construction sites is a critical step toward establishing the feasibility of AR applications for construction sites. The next steps in thisresearch will involve improving ARCam with multi-range calibration that is based on the zoom-dependent camera calibration method of Fraser and Al-Ajlouni (2006).

7. ACKNOWLEDGMENT

This research was made possible by support from the National Science Foundation under Grant No. CMS-0239091. Opinions, findings, conclusions, or recommendations presented in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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