Automatic Calibration of an Optical See Through Head Mounted Display for Augmented Reality Applications in Computer Assisted Interventions

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Abstract We are developing an optical see through head mounted display in which preoperative planning data provided by a computer aided surgery system is overlaid to the optical image of the patient.
In order to cope with head movements of the surgeon the device has to be calibrated for a wide zoom and focus range. For such a calibration accurate and robust localization of a huge amount of calibration points is of utmost importance. Because of the negligible radial distortion of the optics in our device, we were able to use projective invariants for stable detection of the calibration fiducials on a planar grid. The pattern at the planar grid was designed using a different cross ratio for four consecutive points in x respectively y direction. For automated image processing we put a CCD camera behind the eye piece of the device. The resulting image was thresholded and segmented, after deleting the artefacts a Sobel edge detector was applied and the image was Hough transformed to detect the x and y axes. Then the world coordinates of fiducial points on the grid could be detected.
A series of six camera calibrations with two zoom settings was done. The mean values of the errors for the two calibrations were 0.08 mm respectively 0.3 mm.

1 Introduction

Augmented reality (AR) visualization is a very intuitive way of presenting medical image information or planning data from preoperative planning. AR has early been applied to operating microscopes in neurosurgery[6]. The development of faster computers and the increasing quality of small displays made possible the development of head mounted displays (HMD) equipped with AR. Video see through systems and some of their application are described in [13, 17, 9, 16], where the term *"in-situ" visualization* can be found.

In recent years we developed an optical see through HMD, the Varioscope AR and integrated it into the CAS system VISIT. Details and applications can be found in [4, 2, 1, 8, 19, 3].

Head movements of the surgeon during the operation require to change the focal plane and the zoom factor of the head mounted display (HMD) without loosing calibration. Accurate and robust localization of a huge amount of calibration points is important for a variable zoom and focus camera model. The current literature[7] illustrates this fact, in this case more than 4500 points were used for seven zoom and focus steps. Nevertheless a considerable error in calibration of the HMD was encountered.

In the following paper a robust automated fiducial detection method for a camera calibration is described.

Due to the fact that we found our optics to be almost free of radial distortion [2], we were able to use a projective invariant, the cross ratio, to determine the world coordinates of the calibration fiducials on a planar grid.

2 Materials and Methods

2.1 The Varioscope AR

The basis device of our HMD is the Varioscope AF3, an optical head-mounted microscope developed by Life Optics, Vienna (*http://www.lifeoptics.com*). It is equipped with variable zoom and focus and also has autofocus. The Varioscope AF3 was adapted for AR by adding two miniature LC displays with VGA resolution (AMEL640.480.24, Planar Microdisplays Inc., Beaverton, OR) and the necessary projection optics (figure 1). This prototype is referred to as *Varioscope AR*. A more detailed presentation of the design can be found in [2, 7].

In our experimental setup the HMD was equipped with a CCD camera at the eyepiece to provide the image for the automated calibration. The transformation from the CCD camera to the plane where the image projected by the miniature displays can be found had been derived by another camera calibration, see 2.2.

Figure 1. A photograph of a prototype of the Varioscope AR. At the ocular of the base instrument a CCD camera was placed.

2.2 Camera Calibration

We use four coordinate systems: the world system, denoted by x_W is the system of the calibration grid, the source system x_S of the tracker probe mounted to the grid, x_H of the HMD itself, and the camera system x_C which is the coordinate system of a display screen in the HMD. Denoting a rigid body transformation between the systems A and B by T_{AB}, we conclude that for the calibration of the HMD the transformation

$$\mathbf{T}_{HC} = \mathbf{T}_{WC}\mathbf{T}_{SW}\mathbf{T}_{HS}, \tag{1}$$

has to be derived.

In this paper we are mainly interested in the automated derivation of the abovementioned transformation for different zoom and focus values, therefore we concentrate on the derivation of $\mathbf{T}_{WC}$ and the associated effective focal length f. The other transformations are either independent of the zoom and focus settings or are provided by the tracking system, details can be found in[7, 2]. The derivation of $\mathbf{T}_{WC}$ was done using Tsai's camera calibration algorithm as described in [18] using an open source implementation by Reg Willson[4] for the calculations.

2.3 Calibration Grid

The calibration grid requires a pattern consisting of feature points whose locations in the system x_W can be derived using the image of a part of the grid. This can be achieved by applying a projective invariance, the cross ratio[15]. The cross-ratio of four points on a straight line is defined by $CR(A, B, C, D) = \frac{AC}{BC} / \frac{AD}{BD}$, where XY denotes the oriented distance between the points X and Y. The projective invariance of the cross-ratio see figure 2 is a result of elementary projective geometry. An introduction can be found in[11] .

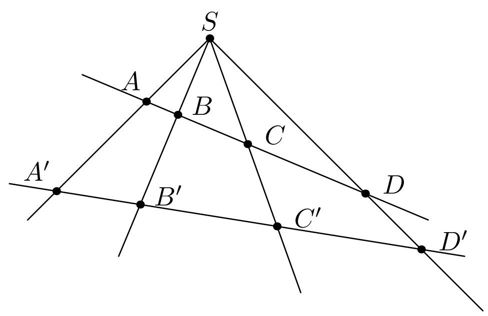

Figure 2. The projective invariance of the cross ratio: $CR(A, B, C, D) = CR(A', B', C', D')$.

[4] URL: *http://www-2.cs.cmu.edu/afs/cs.cmu.edu/user/rgw/www/TsaiCode.html*

Figure 3 shows the grid mounted on the optical table. Four consecutive squares at the x- or y axis of the grid have a characteristic cross-ratio. Therefore the world coordinates of the point can be derived, provided that the axes have already been found. The grid has been made using a scilab (*http://www.scilab.org*) script generating an image which was printed by a Hewlett-Packard Laserjet 4 laser printer.

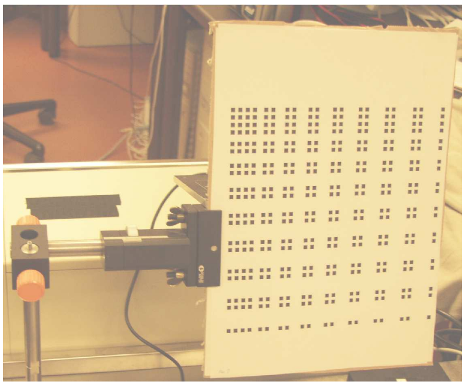

Figure 3. The calibration grid mounted on the optical table

2.4 Image Processing

In order to determine the positions of the calibration points in the x_W system the centers of gravity of the squares and also the x and the y axes in the pattern had to be found. The procedure consists of the following steps, the methods used therein can be found in introductory texts on digital image processing, such as [12, 10]. All programming concerning image processing was done in ANSI C++, using the gnu scientific library *http://www.gnu.org/software/gsl* for calculations and the Qt library *http://www.trolltech.com* for displaying and the graphical user interface, the operating system was SuSE Linux 7.3, the compilation was done using the gnu `c++` compiler `g++`.

- *Thresholding* the image to get a binary image for segmentation
- *Segmentation* is done to differentiate between the pattern and the artifacts caused by noise. This was done using four and eight connectedness of neighboring pixel.
- The *noise removal* step removed all objects found during the segmentation which were smaller than a threshold. The threshold had to be chosen depending on the quality of the image, and remains constant for a series of calibrations provided that the light and the position of the camera is unchanged. These first three steps are illustrated in figure 4.

– The *centers of gravity* of the remaining objects have been calculated.
– Detecting the x *and* y *axes* was done in two steps
  - *Edge detection* using *Sobel* convolution kernels.
  - *Hough transformation* for lines.
– The *point matching* was done using the cross ratio of a point and its three successors in x respectively y direction.

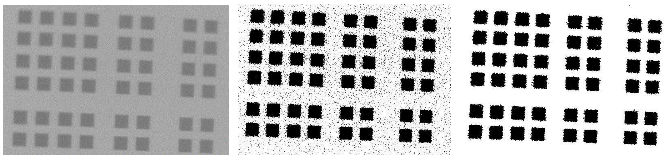

Figure 4. The first figure shows the image provided by the CCD camera, in the second figure the image is thresholded, the third figure is made after removing the smaller objects caused by the image noise. The next steps are calculating the centers of gravity, detecting the x and y axes and at last the points can be associated to their coordinates using the cross value.

3 Results

A series of six camera calibrations with two zoom settings was done. For each zoom setting three different grid positions *A, B, C* perpendicular to the optical axis were used. The distance from the grid to the camera was unchanged in all measurements.

The axes and the fiducial points were detected automatically. The object space error (OSE) averaged over the number of calibration points was calculated according to [20], the results can be found in table1.

grid position	max zoom	min zoom
A	0.07 ± 0.04	0.33 ± 0.27
B	0.07 ± 0.05	0.28 ± 0.21
C	0.11 ± 0.16	0.28 ± 0.2
mean	0.08	0.3

Table 1. The mean OSE errors in mm of the calibrations for two zoom settings (min and max) and three grid positions.

4 Discussion and Conclusions

The Varioscope AR has already been used for cadaver studies [19, 3], but only with a fixed calibrated focus plane and fixed zoom setting. In these studies the achieved overall accuracy did not exceed the limit usual for CAS, which can be found e. g. in [5].

It is not yet possible to mount a camera to the Varioscope AR in a rigid or reproducible way which would be necessary for employing automated calibration methods (Both the calibration of cameras [20] and the operating microscope [6] have a video interface thus both can use an automated calibration). Additionally the zoom and focus settings cannot be reproduced accurate nor measured with the desired accuracy.

Recently Life Optics presented the new Varioscope M5, which broadcasts its zoom and focus settings via the serial interface and has an built in CCD camera. Furthermore zoom and focus can also be set via the serial interface. We already began to adapt the M5 for AR using miniature LC displays with XGA resolution (Kopin Corp, *www.kopin.com*). We want to use this new HMD and an linear positioning device consisting of an linear positioner and a C-560 stepping motor controller from PI Physik Instrumente, Karlsruhe, Germany, which communicates with the PC using a HPIB interface see figure 5

Additionally the design of the grid will be optimized according to[14].

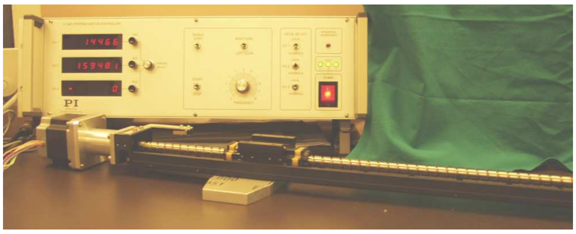

Figure 5. Stepping motor controller from PI and linear positioner.

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