Abstract

Purpose: Current gaze-tracking systems can monitor point of gaze allowing for free head movement, but do not perform well when used with the large display surfaces and wide range of head positions needed for presentation of wide-field experimental stimuli. We developed a novel system for monitoring a subject's gaze, providing accurate eye location and orientation recordings over the large spaces needed for action and motion experiments. This system allows for complete calibration from only a short series of directed gazes and requires almost no physical measurement.

Methods: The gaze tracking system consisted of an ISCAN head mounted pupil tracker and an Ascension Flock of Birds position sensor with Extended Range Transmitter. Data from the position sensor were compensated for magnetic distortion using a polynomial correction function. Gaze was computed based on measurements from the two sensors using a geometric model. The thirteen parameters of the gaze computation model were found using a nonlinear regression technique. The calibration technique was verified using human subjects, and using a laser mounted in a foam mannequin head.

Results: Our implementation of the system allowed for tracking of gaze of subjects walking on a treadmill. Measurements covered a volume of 2 cubic meters. Mean error within this volume was less than 2 degrees. Eye movements were recorded at a rate of 60Hz, limited only by the speed of the ISCAN pupil tracker. Recordings of head position, vector of gaze and exact eye location were made simultaneously.

Conclusions: A flexible, accurate system for recording head and eye movements in response to large stimuli has been developed using standard hardware systems.

Motivation

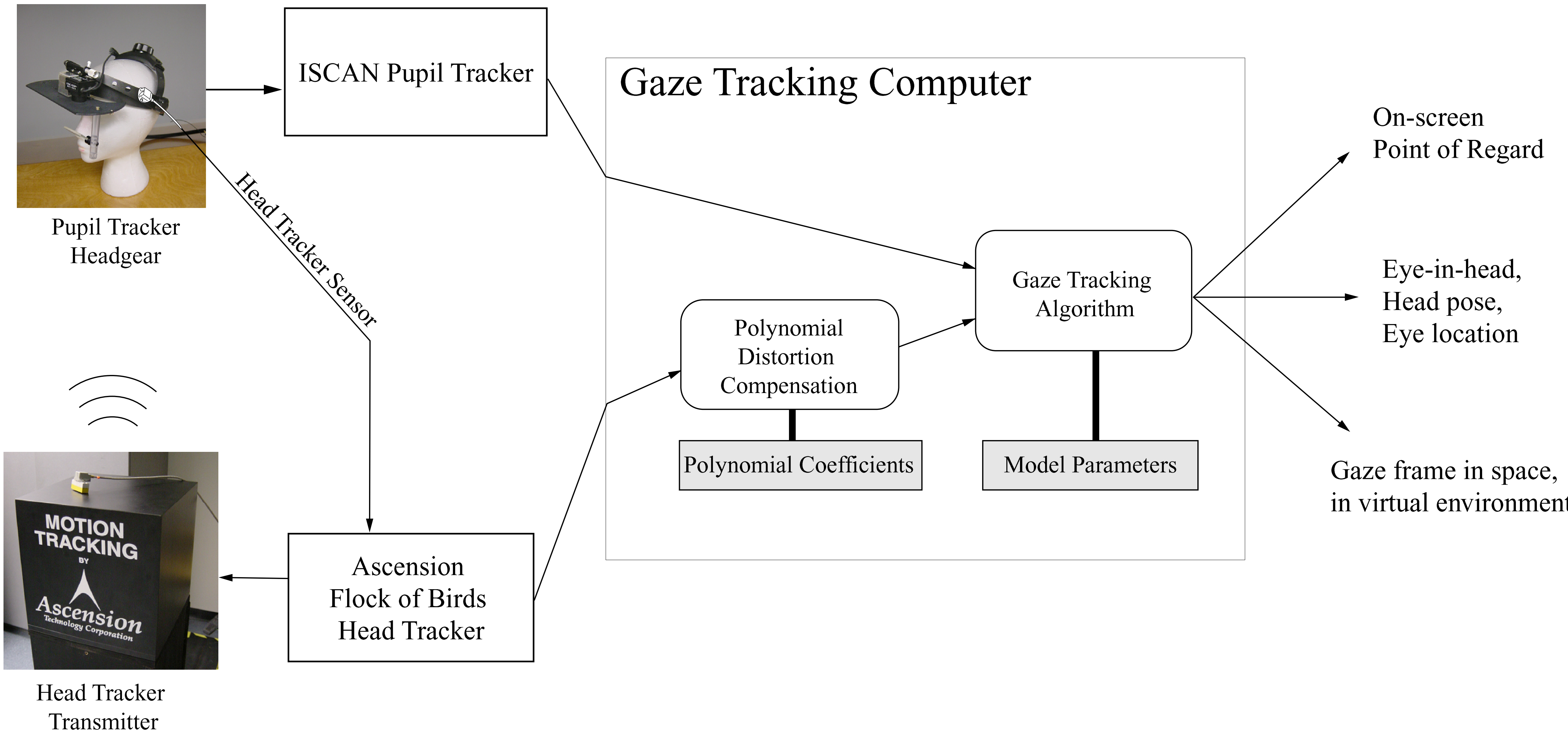
- Combine head tracking and eye tracking to track gaze in 3D or on the surface of the screen
- Gaze tracking system for a Virtual Reality Walking Simulator (subject on a treadmill viewing large display surface)
- Maintain eye-in-head information for evaluation of ophthalmic and other head-mounted devices
- Track eye location with respect to Virtual Reality model

Figure 1: Subject viewing virtual environment while standing on a treadmill. Screen spans 85^{o} at a distance of 36"

Addresses shortcomings of existing gaze tracking systems

- No need for clear line-of-sight to face (remote video trackers)
- No need to hold head still for any part of calibration
- Corrects for distortion in magnetic head tracker data
- No need for screen-mounted optical markers (EyeLink)
- Allows for large range of head and body movement
- Can provide gaze **frame**, not just gaze **vector**:
    - Vector includes direction information only, frame contains roll information in addition to direction
    - Can create head-stabilized images that respond to head roll
    - Retina-stabilized images would be possible with the addition of an eye torsion tracker

System Diagram



Geometric Model

- Model spatial relationships τ as 4x4 transformation matrices
- Relationships combined via matrix multiplication
- Gaze frame $\tau_{O \leftarrow E}$ computed from sensor measurements and 13 calibrated parameters (Step 2)
- Point of gaze computed from gaze frame

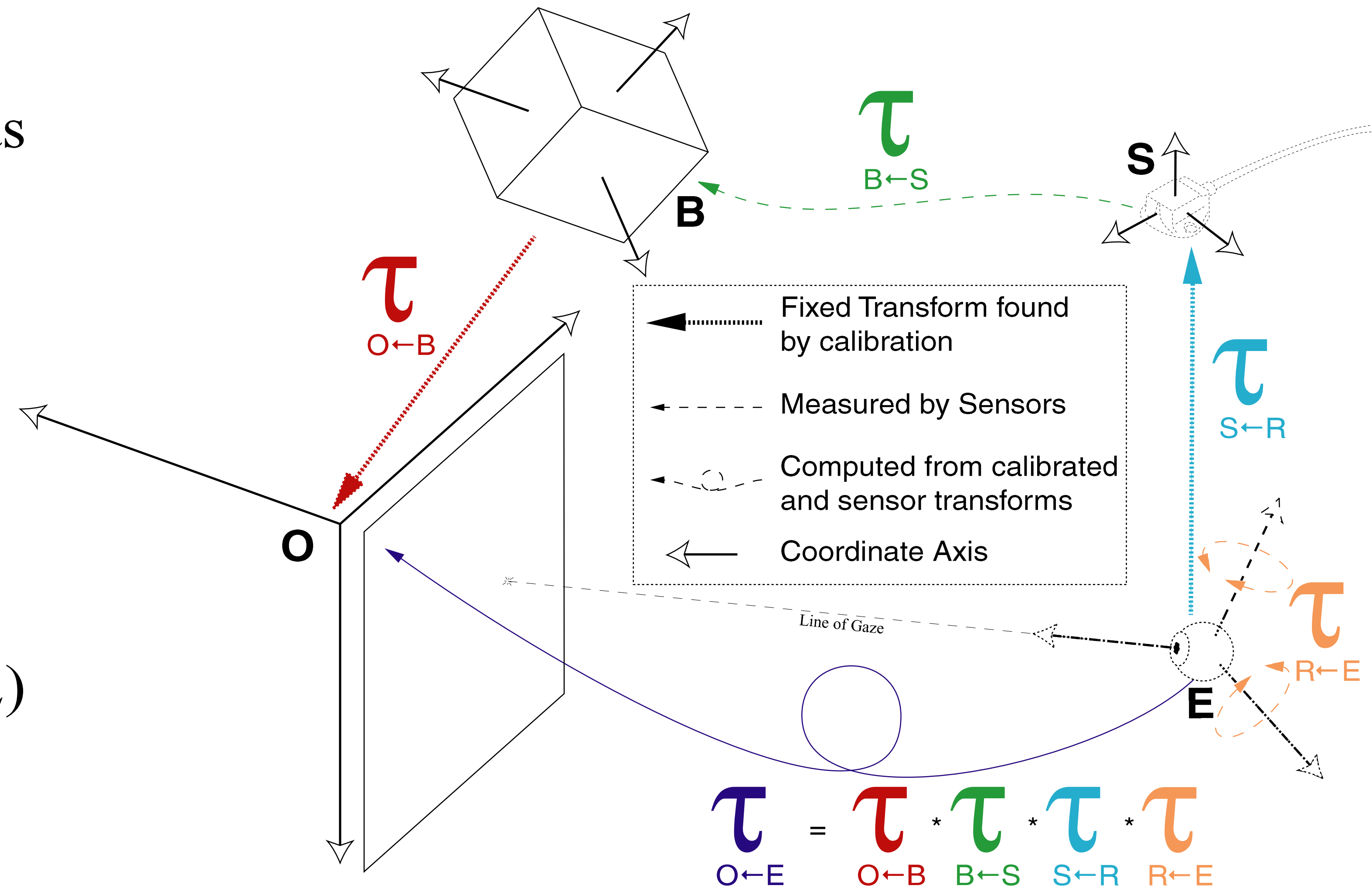


Figure 2: Geometric Model Used to Find Gaze Frame
Coordinate Frames are labelled as follows: **O**: Video Screen, **B**: Head Tracker Transmitter, **S**: Head Tracker Sensor, **R**: Center of Rotation of Eye, **E**: Eye.

Calibration

Background:

Must calibrate system to account for:

1. Magnetic distortion of head tracker
2. Session-to-session differences in headgear placement $\tau_{S \leftarrow R}$ and in location of motion tracker transmitter relative to screen $\tau_{O \leftarrow B}$
3. Location of ISCAN eye camera relative to eye

Procedure:

- Measure magnetic distortion **once** and use to build compensation function
- Calibrate geometric transformation parameters $\tau_{O \leftarrow B}$ and $\tau_{S \leftarrow R}$ using directed gazes **before each session** (fig. 4)
- Calibrate eye tracker using head-stabilized targets **before each session**
- Compute gaze frame, gaze point, eye-in-head position in real time (60Hz)

Calibration Step 1: Distortion Compensation

Head tracker readings are distorted by magnetic interference. This procedure reduces the effect of that distortion[1].

- Record position sensor readings over 3D pegboard grid
- Perform least-squares fit for coefficients a_{ijk}, b_{ijk}, and c_{ijk} of compensating polynomials

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \sum_{i=0}^{d} \sum_{j=0}^{i} \sum_{k=0}^{i-j} \begin{bmatrix} a_{ijk} \\ b_{ijk} \\ c_{ijk} \end{bmatrix} x_o^{\,i}\, y_o^{\,j}\, z_o^{\,i-j-k}$$

- This one-time calibration procedure takes one hour, and is performed whenever the environment is changed

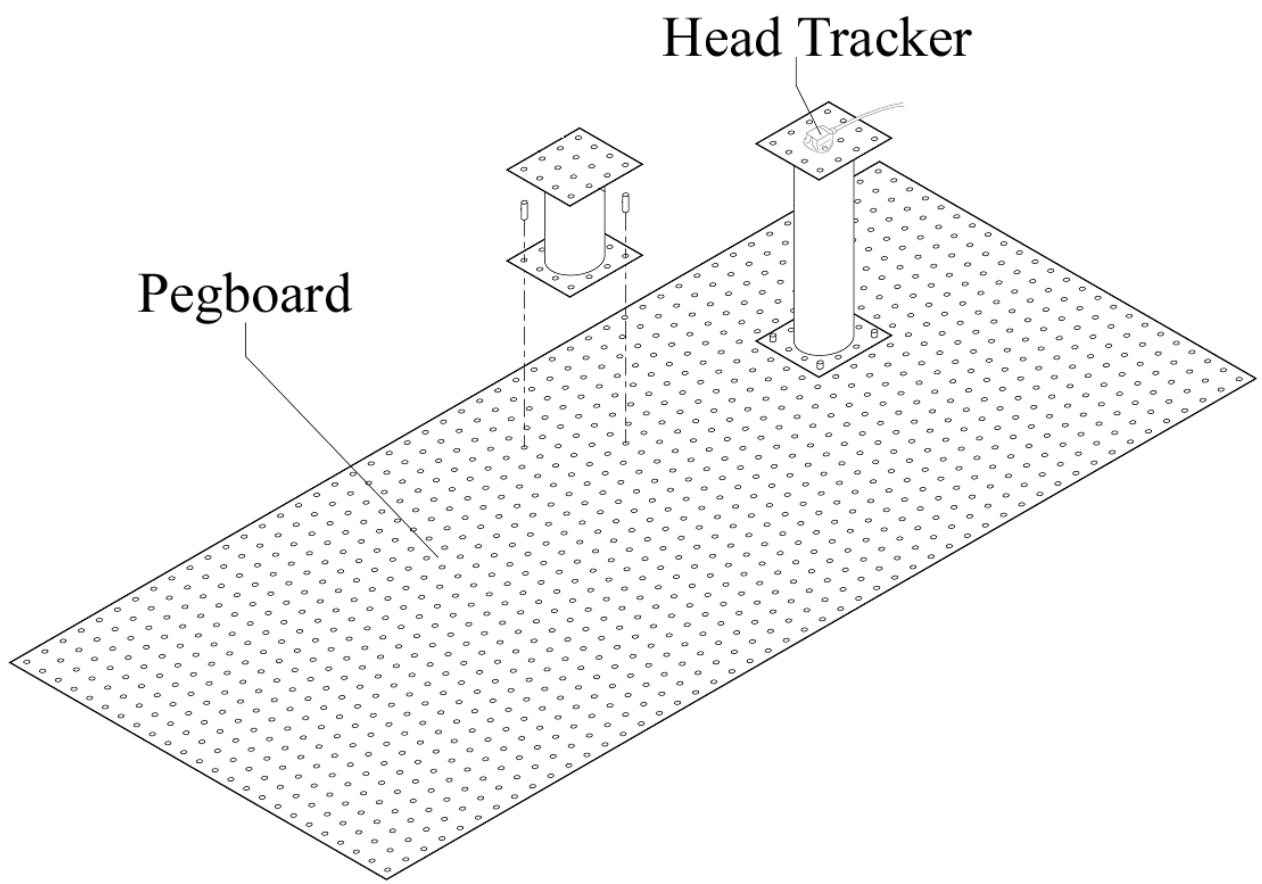


Figure 3: 3D Pegboard system for placing tracker at known locations

[1] Although distortion appears in both position and orientation of head tracker measurements, distortion compensation was performed on position only.

Calibration Step 2: Geometric Transformations

This step discovers the spatial relationship $\tau_{S \leftarrow R}$ between the head tracker sensor and the eye, as well as the relationship $\tau_{O \leftarrow B}$ between motion tracker transmitter and screen image.

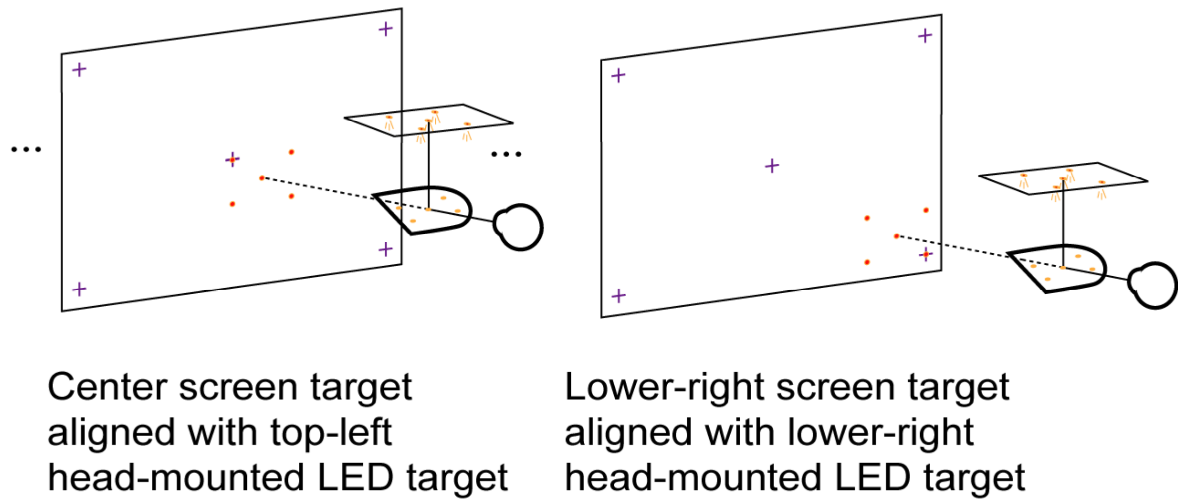


Figure 4: Geometric calibration procedure. Subject aligns combinations of head-mounted and screen targets.

- Subject directs gaze to align combinations of head-mounted LED targets with on-screen targets
- Perform non-linear regression to find 13 transformation parameters consistent with directed gazes
- This calibration procedure takes about one minute, and is performed once per session

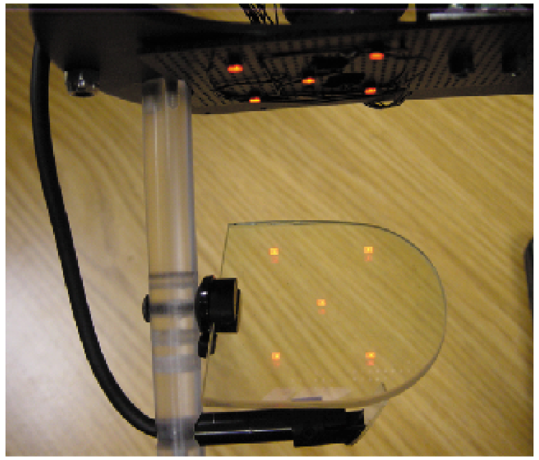


Figure 5: Head-mounted LED fixation targets

Calibration step 3: External Eye Tracker

This calibration allows the eye tracker (ISCAN) to report eye position relative to the head. The head-mounted ISCAN system requires that the subject view a sequence of stationary targets[2]. Once calibrated, the output of the ISCAN system is used to construct the $\tau_{R \leftarrow E}$ measurement.

- Use geometric model (fig. 2) to place head-stabilized eye tracker calibration targets on screen
- Calibrate eye tracker as subject views five or nine stabilized targets
- This procedure takes a few seconds, and is performed once per session

[2] ISCAN calibration data may also be collected concurrently with step 2, as subject views head-mounted fixation targets.

Validation Study

- Gaze tracking system was calibrated using steps above
- Twenty-five validation gazes were performed from arbitrarily chosen locations within the envelope of the head tracker
- Actual gaze points were compared with computed gaze points (fig. 8)
- For comparison, first and/or second calibration steps were omitted using same data (fig. 7)

Step 1

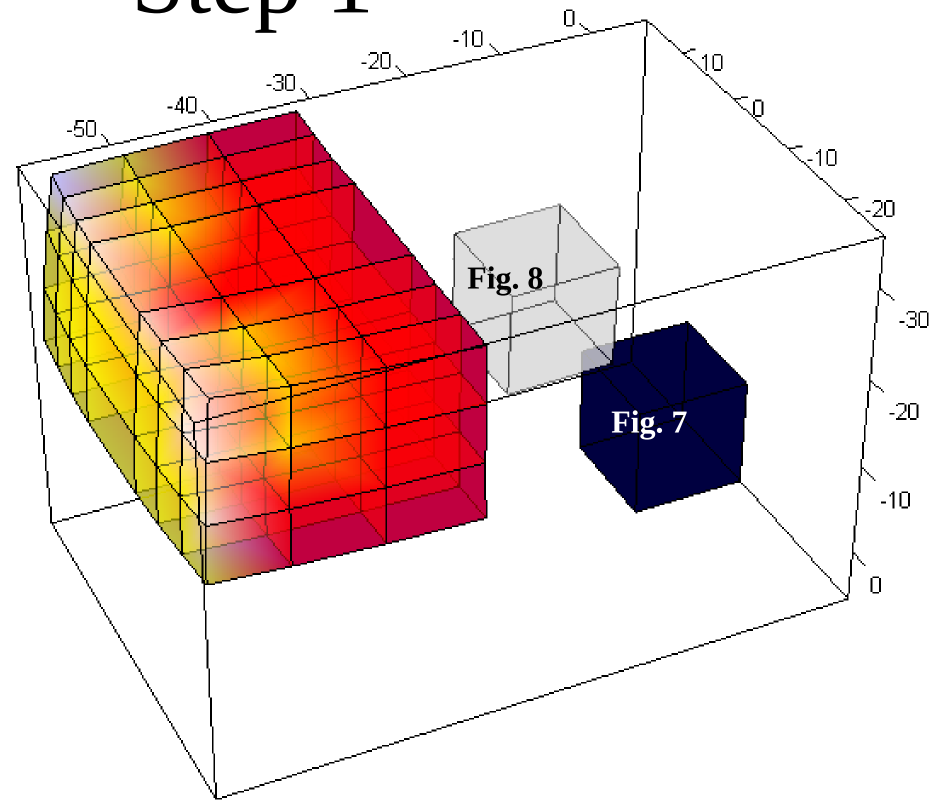
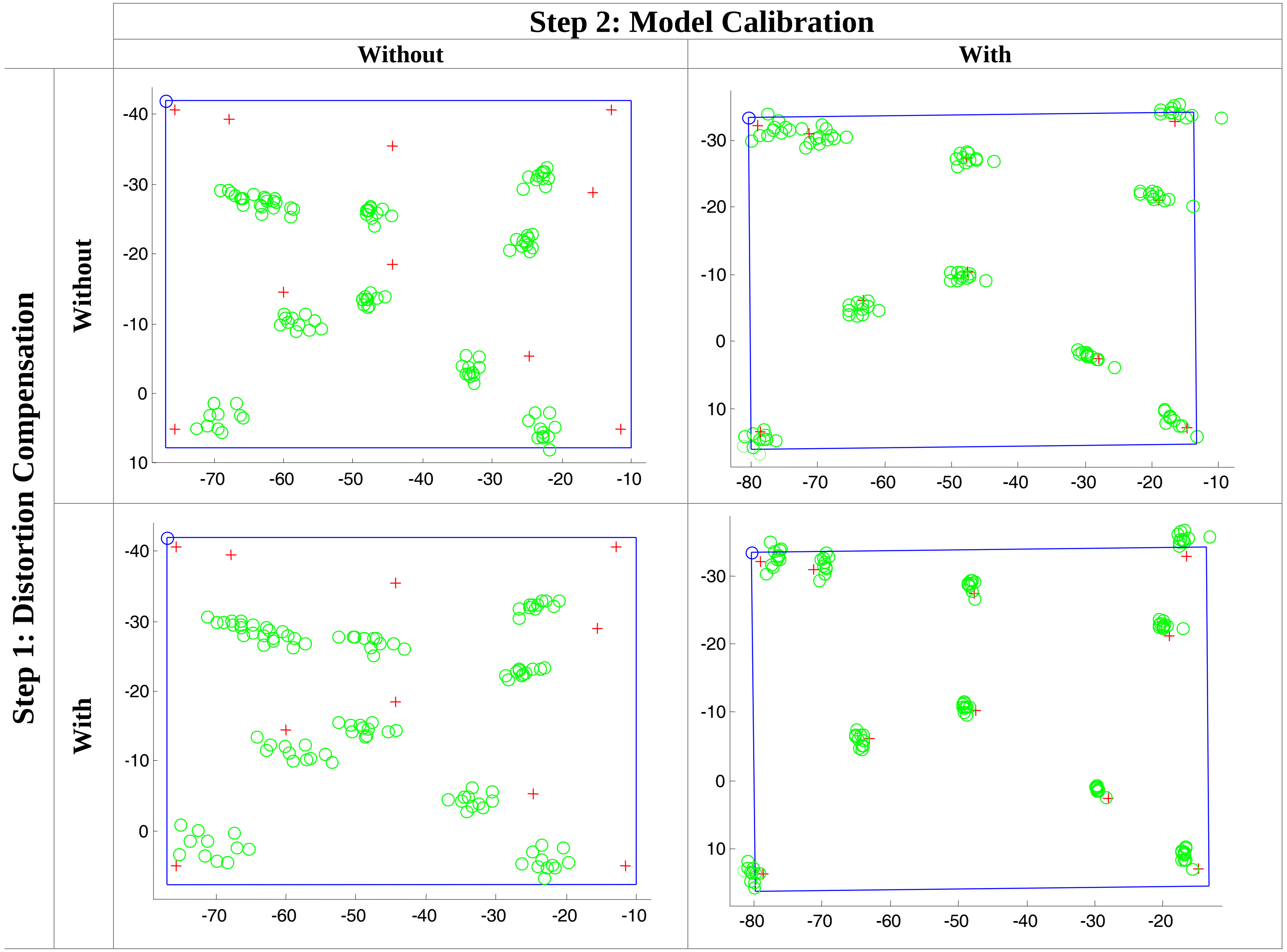


Figure 6: Distortion measured in calibration step 1. Plot shows reported locations of head tracker when placed at 128 locations on 3D pegboard. Units are inches in coordinate system of head tracker transmitter (black cube). Yellow areas have error of up to six inches.

Results

Steps 1 and 2



gure 7: Model-predicted screen intersections of gaze line omitting calibration steps one and/or two for subject looking through center ad-mounted LED target (no eye movement). Axes are labeled in coordinate system of head tracker transmitter, units are inches. Red osses are actual gaze point. Green circles are predicted gazes from eleven viewing locations.

Step 3

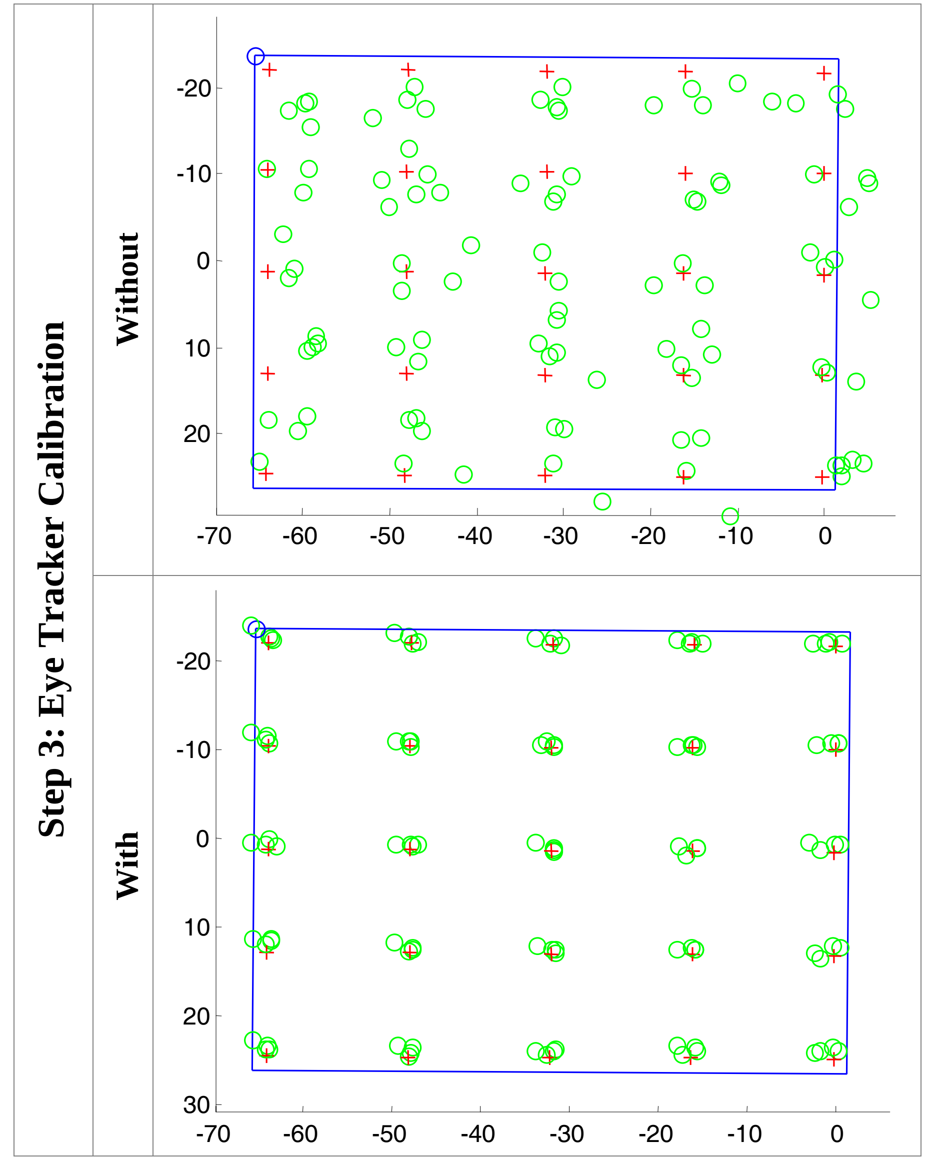


Figure 8: Model-predicted screen intersections of gaze line with and without eye tracking. Data for 100 gazes each from a different viewing location. Motion tracker transmitter was moved closer to measurement space (fig. 6)

Conclusions

- Proposed gaze tracking system computes gaze point on large display surface from many positions more accurately than without calibration.

- Calibration step 1 (Distortion Compensation) may not provide significant benefit if steps 2 and 3 are performed.

Acknowledgement

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