Automated techniques for characterizing and testing helmet mounted displays

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ABSTRACT

With ever-increasing applications for Helmet Mounted Displays (HMD) and current high-volume production rates, the development of automated measurement equipment and techniques for characterization and testing displays becomes paramount to delivering a consistent and quality product. This paper examines the requirements that drive the need for automated HMD testing and the interrelationships that exist between the design of the prime hardware and its test equipment.

Topics presented include the following:

- Design of an automated optical measurement bench that maximizes the use of COTS hardware and software and is readily adaptable to different HMD designs.
- Specialized tooling requirements.
- Methods of achieving HMD alignment to the optical Line of Sight (LOS).
- Development of reusable test software components.
- Algorithms for predicting the location of images in the HMD reference frame, including coordinate transformations and search algorithms.

Issues concerning characterization of image sources and optical components are presented utilizing case studies. Actual production throughput data is compared with data from more traditional test methods to emphasize the advantages of this approach. Finally, actual results of achievable accuracy using the automated optical measurement bench are presented.

Keywords: helmet display, HMD, display characterization, display testing

1. INTRODUCTION

As modern Helmet Mounted Displays (HMD) move from the development phase to production, the need for automated testing to ensure the performance, quality, and constancy of the product becomes paramount. Constraints of power, weight, and center of gravity (CG) have forced the optical designer to make compromises in the optical performance. Overcoming these deficiencies requires an accurate, stable, and repeatable measurement system to allow characterization of the optical path, thus enabling electronic distortion correction in the display-processing unit. The testing process for HMDs should be developed concurrently with the display system design. Achieving the goal of accurate and repeatable testing with high throughput will only be possible if the HMD designers and test equipment engineers work in concert.

This paper covers the development of an automated optical bench as well as characterization and testing of two different HMDs at Kaiser Electronics. The first is a monocular, CRT based, off-the-visor HMD (M-HMD) while second is a bi-ocular, LCD based HMD (B-HMD) utilizing a single element combiner for each eye.

2. AUTOMATED OPTICAL BENCH DESIGN

The development of an automated HMD test station at Kaiser Electronics grew out of the needs of the M-HMD program. An aggressive delivery schedule shifted the focus from the procurement of an end product to the development of an interim test station. The goal was to have a semi-automated test station available within six months while the final test station was in development. This aggressive schedule drove the requirements for the interim design that ultimately led to a final design, forming the basis for testing HMDs at Kaiser Electronics.

Although each specific HMD design imposes unique constraints on its testing, common elements can be applied to the design of an automated optical characterization and test bench. The HMD unique elements can then be handled as sets of specialized tooling.

In simplified terms, an automated optical bench must be capable of providing accurate and repeatable positional, line width, and luminance measurements under computer control. Functionally, it should be equivalent to a combination theodolite and photometer. Additionally, it must have a movable stage allowing the sensor to be positioned precisely at the design eye of an optical system under test. The ability to provide focus, gain, and aperture control is also desirable. When testing HMDs with registration accuracy on the order of 3.0 milliradians (mr), optical bench positional accuracy and repeatability should be better than or equal to 0.3 mr and 0.1 mr respectively.

The M-HMD program chose to design its test system using an automated optical bench from Spectron Engineering of Denver Colorado. This optical bench received limited use by a previous program at Kaiser Electronics. M-HMD was the first program to fully exercise the capabilities of this optical bench and many of the lessons learned during this program have been applied to the B-HMD program. As originally designed, the optical bench had most of the features and performance required by Kaiser for testing HMDs. It functioned as a theodolite and photometer under computer control and included a robust command set for measuring and analyzing data. The "sensor head" consisted of a small mirror projecting an image onto a CCD camera mounted co-axially and had a field of view (FOV) of approximately 1.3 degrees. The mirror was small enough to be inserted inside a helmet so that it could be used for designs based on either a fully integrated helmet-display or more modular designs with a separate display unit and helmet. The mirror was adjustable $\pm$ 25 degrees in elevation and its assembly rotated $\pm$ 30 degrees in azimuth. Additionally, an x, y, z transport allowed motion of the sensor head $\pm$1.75 inches in each axis, sufficient for all types of HMD products at Kaiser Electronics. The specified accuracy and repeatability also met Kaiser's requirements. The optical bench, shown in Figure 1, was mounted on a vertical stand or "tombstone". Aside from providing a very stable base, this mounting arrangement facilitated the attachment of both the HMD and hard tooling to the bench.

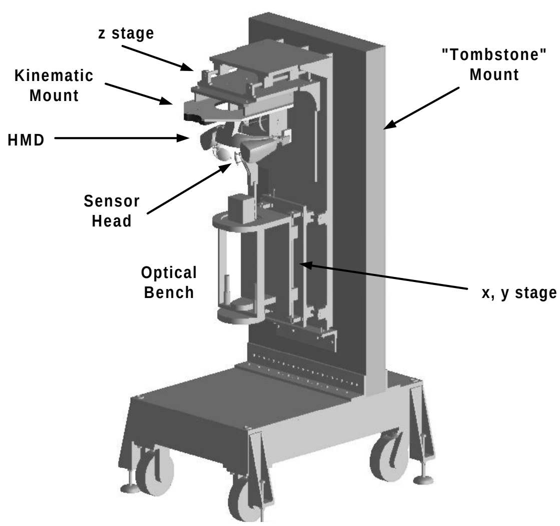

Figure 1 - Optical Bench with Vertical Stand

2.1 HMD tooling

HMD unique hard tooling allowed adaptation of the automated optical bench to specific HMD designs. Employing a kinematic mount enabled rapid setup and teardown of the hard tooling without tedious alignment procedures, thus facilitating usage of the same optical bench by different programs. Although both HMDs are radically different designs, they had some common tooling requirements. Each display unit required an optical bench mounting assembly and a reference reticle. The reference reticle was a collimated backlit reticle with a large number of crosshairs (~220 for M-HMD and ~800 for B-HMD). It was used for characterizing the see-through distortion of visors or combiners and for providing a "real" world reference for registration (overlay) testing. The B-HMD reference reticle is shown in Figure 2.

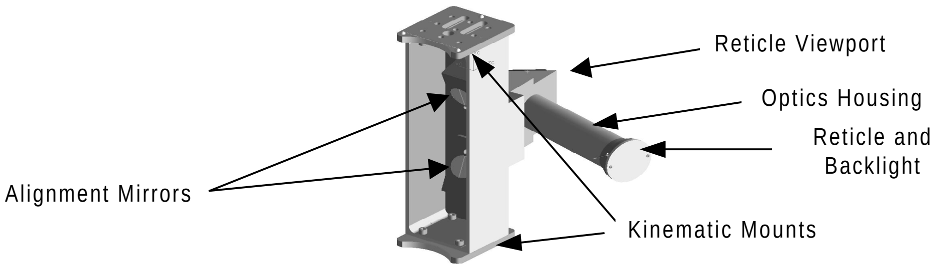

Figure 2 – B-HMD Reference Reticle

Several types of hard tooling were unique to the HMD design and program requirements. A goal of the M-HMD program was interchangeability for CRTs, relay optics assemblies, and visors. This required each component to be characterized independently and created the need for additional tooling. The visor tool was the simplest, consisting of a mounting structure that emulated the display unit visor receptacles. Two other tools, a CRT and a relay optics characterization tool were also developed. These are shown pictorially in Figure 3.

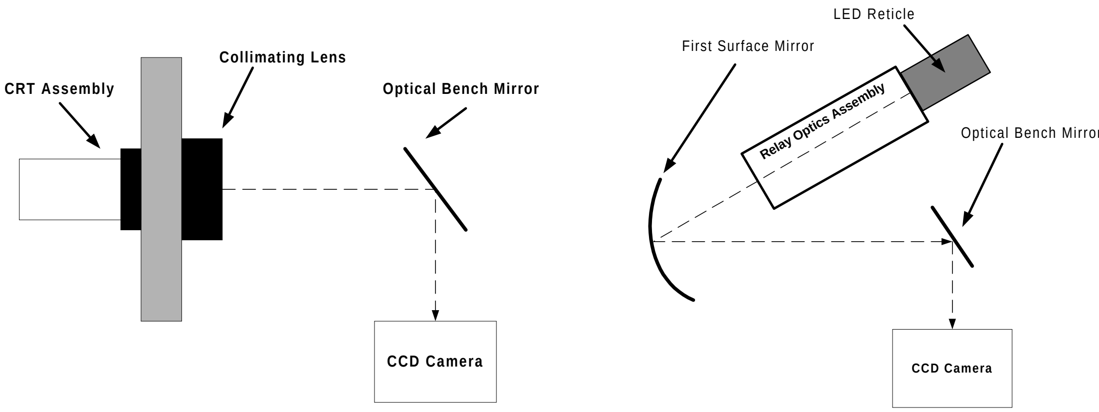

Figure 3 – Diagram of CRT and Relay Optics Tools

The B-HMD requirement for factory boresighting instead of on-aircraft boresighting created the need for additional hard tooling. This tool, the display unit Master Tool, was designed for two purposes. Firstly, it was used to establish the optical Line of Sight (LOS) for the display unit. Secondly, it was used to transfer the optical LOS to another test bench for boresighting the magnetic head tracking system LOS, allowing both to be aligned to each other and to the airframe. The display unit Master Tool, shown in Figure 4, contained a set of mirrors for aligning the display unit mounts on the optical and tracker benches using a theodolite.

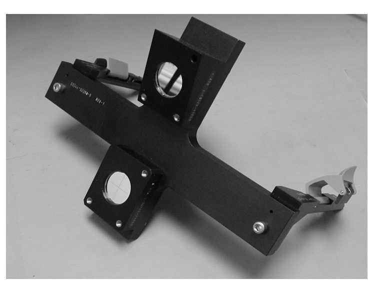
Figure 4 – Display Unit Master Tool

2.2 Electronics

An electronics rack was required to generate the display signals, provide power and I/O for the HMD, and to control the optical bench. This electronics rack made use of commonly available Commercial-off-the-Shelf (COTS) components. The optical bench was available with a rack mountable IEEE-488 compatible controller. To achieve commonality in design and allow for future upgrades, a rack mountable PC compatible workstation running a version of the Windows™ operating system was chosen as the "heart" of the test station. The workstation was provided with sufficient expansion card capability to support the testing requirements. PC compatible circuit cards were used for industry standard interfaces (GPIB, EIA-422, Ethernet, I^2C, EIA-232, etc.) as well as for data acquisition and image capture. Figure 5 shows a functional block diagram similar to the actual interim design.

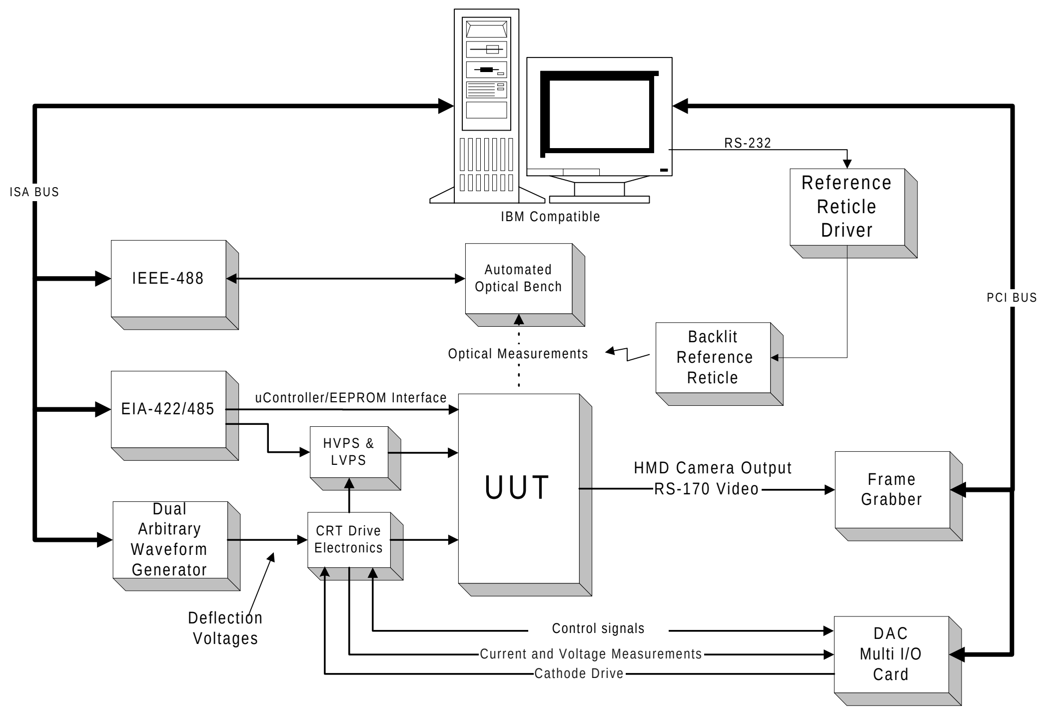

Figure 5 – Interim Factory Test Equipment Block Diagram

For proprietary or highly specialized interfaces, however, it became necessary to design hardware providing these functions. Display drive interface requirements presented a unique challenge in the design of test equipment since they are highly dependent on the display technology used and system constraints.

The M-HMD display source was a miniature CRT of unique design. In order to provide the appropriate deflection and cathode signals, the drive electronics from another HMD program was modified to interface between an arbitrary waveform generator and the HMD, as shown in Figure 5. CRTs require a display drive subsystem that monitors the high voltages, drive signals, and beam deflection in order to prevent burn spots on the phosphorous. For this reason, the final version of the test equipment utilized a custom designed drive circuit and High Voltage Power Supply (HVPS) incorporating phosphor protection circuitry. A rack mounted PC compatible workstation with COTS expansion cards was still used to control the drive circuits and the optical bench. A block diagram of this design is shown in Figure 6.

The B-HMD used two LCD micro-displays as the display sources. The HMD utilized a proprietary Low Voltage Differential Signaling (LVDS) interface that enabled the development of a very low power (<1.25W) and light weight miniature electronic LCD drive circuit composed of discrete COTS components. In order to retain a COTS design for the display drive in the test equipment, a small interface board was designed converting the output of a PC compatible PanelLink™ video card to the unique LVDS format. Figure 7 provides a block diagram representation of the test equipment to HMD interface.

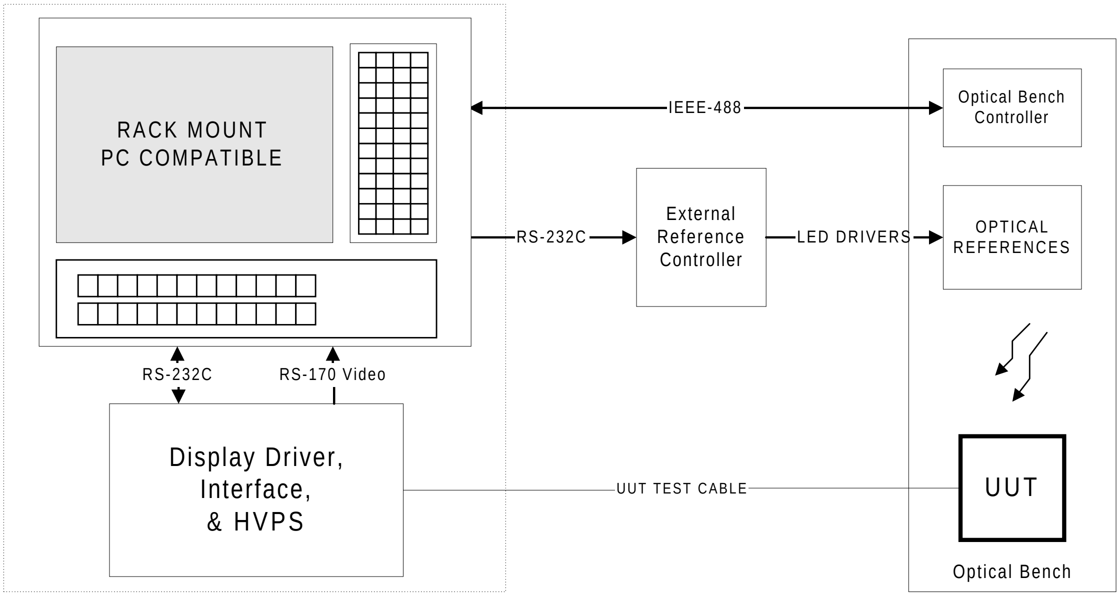

Figure 6 – M-HMD Factory Test Equipment Block Diagram

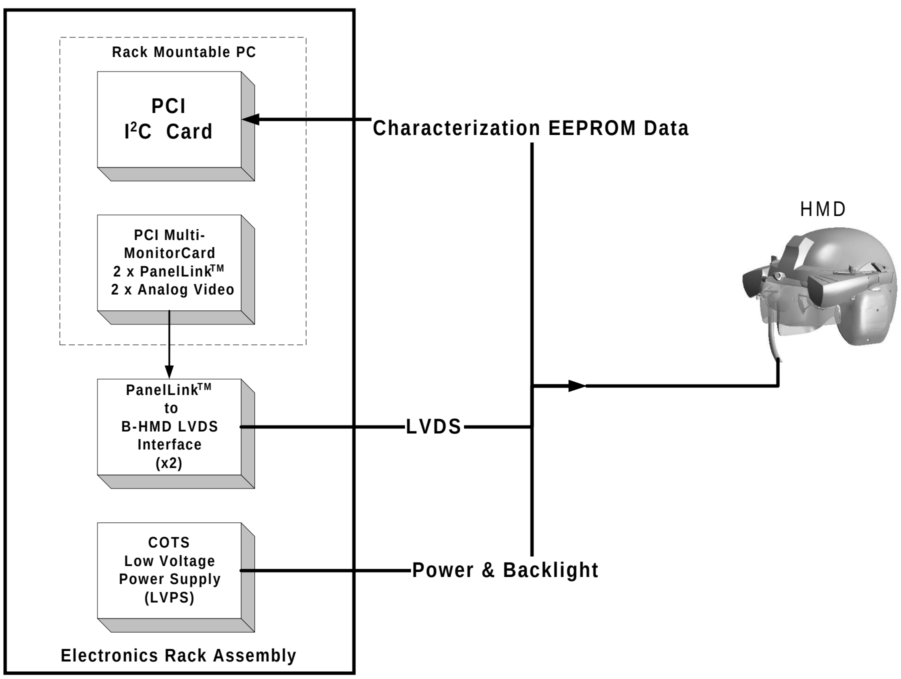

Figure 7 – B-HMD Test Set Display Drive Interface

2.3 Software

The control software selected to drive the test equipment rack electronics and the automated optical bench was National Instruments' LabView™. LabView™ was chosen for several reasons in addition to its wide popularity in the test equipment community. Firstly, it offered a robust set of tools for controlling instrumentation including COTS drivers for a variety of industry standard circuit cards, from ISA, to PCI, to VXI, etc. Secondly, it provided the ability to perform both advanced mathematical operations and sophisticated image processing through add-on tool sets. Thirdly, it provided the capability to easily write drivers for custom equipment and lastly it supported a hierarchical software development process providing reusable code modules. Many of the software modules (called Virtual Instruments or VIs) used on the B-HMD program were “borrowed” from work performed on M-HMD. The development approach specified the Human Machine Interface (HMI) in terms of controls, indicators, and their functions and allowed the software engineer some leeway to design these within the constraints of human factors guidelines. For detailed processes such as characterization, a flow chart provided the sequence of events for the software designer to code.

3. MEASUREMENT TECHNIQUES

3.1 Coordinate system relationships

Measuring points with the optical bench and relating those measurements to alternate reference frames (e.g., HMD, external reticle, or “real” world) requires coordinate transformation. The coordinate transforms are the key to the ability to measure meaningful data.

The coordinate system as viewed in the optical bench reference frame (i.e., pilot's point of view) uses the following convention as shown in Figure 8.

+x = right   +y = up   +z = straight ahead   (where x, y, and z are represented by direction cosines.)

For azimuth and elevation coordinates, azimuth can be defined as the angle the direction vector makes when projected in the x-z plane with positive angles corresponding to positive x direction cosines. Elevation can thus be defined as the angle the direction vector makes when projected in the y-z plane with positive angles corresponding to positive y direction cosines.

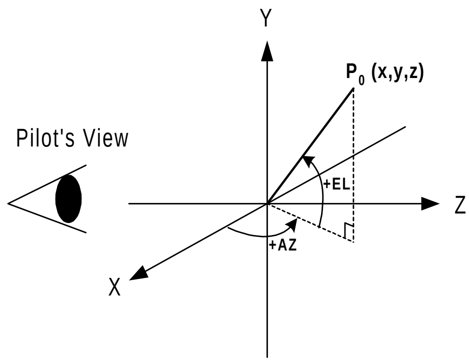

Figure 8 – Optical Bench Coordinate System

To convert azimuth and elevation coordinates into direction cosines (i.e., a unit direction vector pointing with the azimuth and elevation coordinates of α and ε) or direction cosine coordinates (x, y, z) into azimuth and elevation coordinates, the following vector transformations can be used.

$$W(\alpha,\varepsilon) := \begin{pmatrix} \cos(\varepsilon)\cdot\sin(\alpha) \\ \sin(\varepsilon) \\ \cos(\varepsilon)\cdot\cos(\alpha) \end{pmatrix} \tag{1}$$

Where **W** is the transform matrix that converts azimuth and elevation angles to direction cosines.

And:

$$D(x, y, z) := \begin{pmatrix} \operatorname{atan}\left(\frac{x}{z}\right) \\ \operatorname{asin}(y) \end{pmatrix} \tag{2}$$

Where **D** is the transform matrix that converts direction cosines to azimuth and elevation angles.

3.2 Coordinate transformation

Applying Euler's rotation theorem, which states that any rotation may be described using three angles, the rotations can be written in terms of rotation matrices $\mathbf{M_1}$, $\mathbf{M_2}$, and $\mathbf{M_3}$ such that a general rotation **R** can be written as:

$$R = M_1 \cdot M_2 \cdot M_3 \tag{3}$$

Using a "roll-pitch-yaw" convention for the Euler angles, where ψ is roll, θ is pitch, and ϕ is yaw, the three matrices can be represented as:

$$M_1 = M_{Roll} = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$M_2 = M_{Pitch} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix} \tag{5}$$

$$M_3 = M_{yaw} = \begin{bmatrix} \cos(\phi) & 0 & -\sin(\phi) \\ 0 & 1 & 0 \\ \sin(\phi) & 0 & \cos(\phi) \end{bmatrix} \tag{6}$$

Two sets of transforms can now be defined to convert coordinates systems. The first set transforms points from the optical bench reference frame to an external reference frame.

$$\begin{bmatrix} P'_x \\ P'_y \\ P'_z \end{bmatrix} = R \cdot \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} \tag{7}$$

Where the points ***P*** (expressed in direction cosines using the ***W*** transform of Equation 1) are the measured points from the optical bench reference frame and the points ***P'*** are the transformed points in the external reference frame.

The second transform is simply the inverse that converts points in the external reference frame to the optical bench reference frame.

$$\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = R^{-1} \cdot \begin{bmatrix} P'_x \\ P'_y \\ P'_z \end{bmatrix} \tag{8}$$

Where $\boldsymbol{R^{-1}}$ is the inverse rotation matrix.

The ***D*** transform in Equation 2 can be used to convert the direction cosines back to azimuth and elevation coordinates. These mathematical transforms were easily implemented as LabView™ VIs for reusability. An example of the Coordinate Transform VI (Equations 7 and 8) is shown in Figure 9.

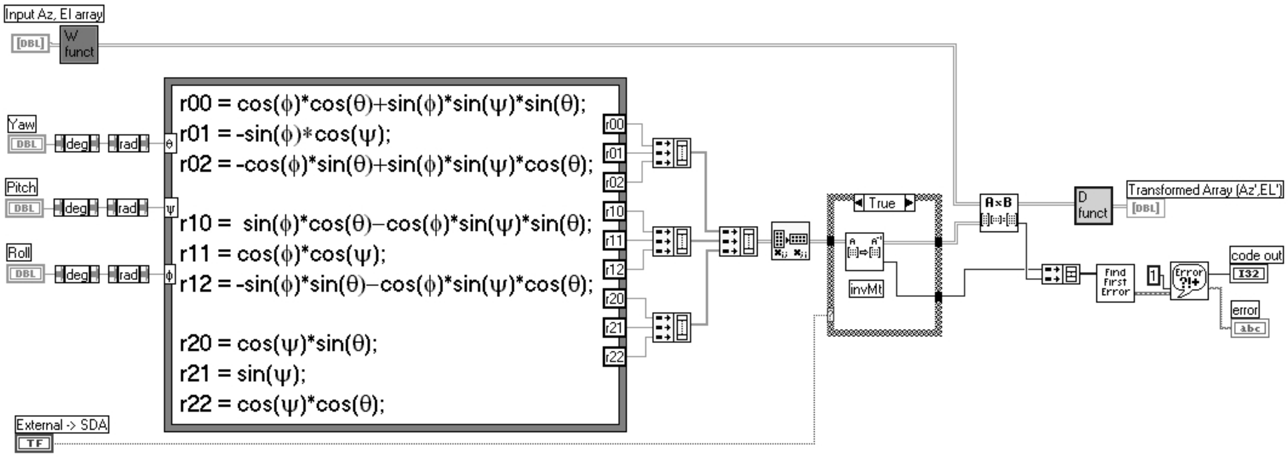

Figure 9 – Coordinate Transform VI

It cannot be overemphasized that transforms are a key and somewhat confusing element. One method of keeping the coordinate systems "straight" would be to color-code the flowchart process used to guide the software developer.

3.3 Photometric Harmonization

The optical bench was factory calibrated for luminance measurement using a white light source. Measuring HMDs having display source wavelengths at ~540 nm required the use of a photometric transfer standard. This standard can be any collimated light source of appropriate wavelength. The transfer standard was first measured using a standard photometer and then re-measured on the optical bench. A correction factor was then entered into a test software configuration file, allowing a wavelength corrected luminance measurement.

3.4 Boresighting

Fundamental to the use of HMDs in targeting applications is the establishment of both optical and head tracker boresight and their alignment with the aircraft systems. While there are several possible approaches, the two most common are on-aircraft boresighting and fixed or factory set boresight.

On-aircraft boresighting requires a Head Up Display (HUD) or an aligned, fixed boresight reticle to project a collimated symbol or crosshair. Once acquired by the pilot and overlaid with a symbol on the HMD display, a simple press of a button allows the optical LOS to be aligned with the head tracking system LOS and the aircraft systems. Thus, it was not necessary to pre-determine the optical LOS of the M-HMD since it was boresighted in the aircraft. Once the zero deflection spot was located, all other measurements were made relative to that location.

The B-HMD however, was required to operate without the use of an aircraft boresight reticle or HUD. Achieving a factory boresight involved establishing a "system" LOS at Kaiser Electronics. This task required the use of the display unit Master Tool. The display unit mount on the optical bench was aligned using a bright line theodolite and the display unit Master Tool as shown in Figure 10. The theodolite was set up at the "system" LOS and using the tool mirrors, the mount was aligned. Additionally, the optical bench was used to measure the yaw (*y*), pitch (*p*), and roll (*r*) of the theodolite from the optical bench reference frame and the values were stored for later use. These values were referred to as the System '*YPR*'. The same tool was then transferred to the tracker alignment bench to align its components to the "system" LOS. Boresighting the head tracking system was accomplished by emulating the aircraft mounting and spatial relationships of the magnetic source and HMD mounted sensor.

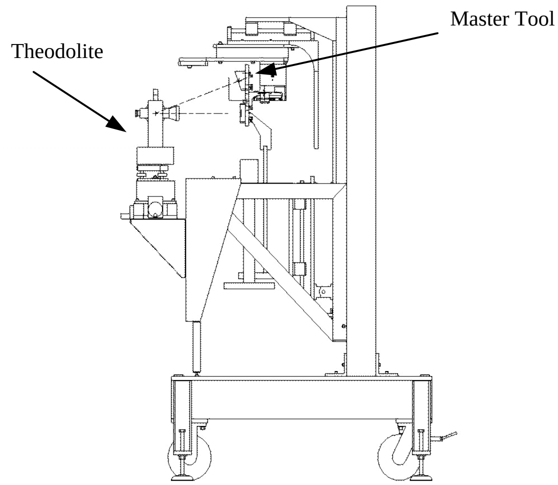

Figure 10 – B-HMD System Boresight Setup

3.5 Reference reticle calibration and "soft" boresight

Two important procedures need to be performed prior to characterization or test. The first is finding the locations of the reference reticle crossings with respect to the optical bench reference frame and storing them for future use. This process can be performed periodically as part of a calibration or maintenance cycle unless the reticle or the reticle mount is damaged or replaced. It consists of first measuring a number of points on the reference reticle using a theodolite, and then measuring all the points using the optical bench after performing a "soft" boresight. The "soft" boresight is a measurement of the yaw, pitch, and roll of an external image plane that provides for coordinate transformation to and from that plane. This procedure can be used every time positional measurements are made to partially compensate for reticle and HMD mount alignment tolerances. The difference between the theodolite measured reticle points and the equivalent optical bench measured points provides a means to measure any drift in the optical bench over time and is useful for determining maintenance cycles as well as ensuring valid test data.

3.6 Positional measurements –Algorithms

Two types of algorithms can be employed when making positional measurements with the optical bench. The first, requiring no special knowledge of the distortion characteristics is a search algorithm. One such useful algorithm is a spiral search, where the optical sensor LOS is moved about a point in an outward spiral while keeping the step size such that the sensor FOV slightly overlaps on each successive step. This algorithm is particularly useful for finding the zero deflection or spot landing point on a CRT. Another search algorithm is based on a linear approximation. If the assumption can be made that over a very small area in the image plane (~ 1-2 degrees) distortions are linear, then a search algorithm can be developed that predicts a new point $\boldsymbol{P'}$ by measuring the slope and distance between the previous two points $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$ and extrapolates to the new point. By keeping the distance between successive points regular and slightly greater than the optical sensor FOV, the probability of finding the next point without ambiguity can be improved. This algorithm works particularly well if the vertical and/or horizontal axis points are found first. Starting from known points on an axis and scanning only in one direction prevents "getting lost" at the edges of the HMD optical FOV. This algorithm can be combined with the spiral search when an expected crossing point is not found or to find the initial starting point (center).

The other type of algorithm uses *a priori* knowledge of the distortion. This knowledge can be obtained by using nominal distortion data obtained from optical modeling software such as Optical Research Associates' CodeV®. Using the CodeV® data as an input file to the coordinate transform and the yaw, pitch, and roll of the reticle or display being measured, the new coordinates can be predicted in the optical bench reference frame. This algorithm has proven particularly useful with the B-HMD.

3.7 Luminance measurements

The optical bench provided the ability to directly measure luminance via its command set. This measurement was corrected in the LabView™ test software by applying the photometric transfer factor previously described. As an alternative to using the built-in optical bench commands, the raw CCD sensor data could be read out via the IEEE-488 interface and image processed with LabView™.

3.8 Line width measurements

The optical bench also included commands to measure line width. As with the luminance measurements, line width could also be determined using LabView™ image processing on the raw CCD data.

3.9 Optical distortion characterization

The M-HMD was characterized at the component level of CRT, visor and relay optics. Measuring the points on the reference reticle with the visor in the "up" position and then measuring the same points with the visor in the "down" position characterized the see-through distortion of the visor. The collected data formed a set that related the "true" coordinates of the reference reticle crossings to corresponding points as seen through the visor. The CRT was mounted in the CRT tool and a spot was moved across the display surface by incrementally stepping the deflection currents. The data provided a map of the CRT image plane as a function of deflection current. The relay optics assembly was similarly characterized with its tooling, providing a map of off-the-visor locations as a function of CRT image plane locations.

Combining the data to provide an end-to-end characterization utilized the following process:

1. A 6^{th} order polynomial bi-variate regression fit was performed on each data set, generating two sets of 28 polynomial coefficients per data set.
2. The azimuth and elevation of reference reticle crosshairs as viewed off-the-visor in the optical bench reference frame was computed by evaluating a 6^{th} order polynomial using the coefficients from the visor see-through distortion regression fit and the actual reference reticle locations.
3. CRT image plane coordinates for each set of azimuth and elevation angles found in step 2 were computed by evaluating a 6^{th} order polynomial using the coefficients from the relay optics regression fit.
4. The deflection current values for the coordinates obtained in step 3 were computed by evaluating a 6^{th} order polynomial using the coefficients from the CRT regression fit.
5. The end-to-end characterization coefficients were obtained by performing a regression fit using the actual reference reticle locations as the independent variables and the deflection currents as the dependant variables.

All of these mathematical steps have been implemented as LabView VIs. An example is shown in Figure 11.

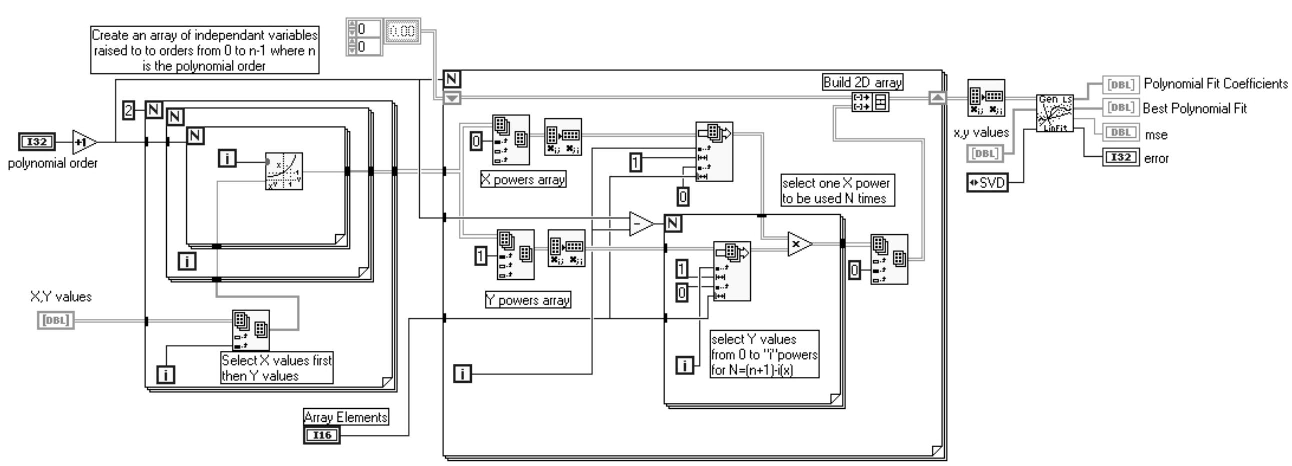

Figure 11 – Polynomial Bi-variate Regression Fit VI

Characterizing the B-HMD was very similar to M-HMD with the exception that it was characterized as a complete unit. Figure 12 depicts the process used to characterize the combiner see through distortion and the relay optics. Since LCD cells exhibit precise geometry and are inherently distortion free, the display source was not characterized.

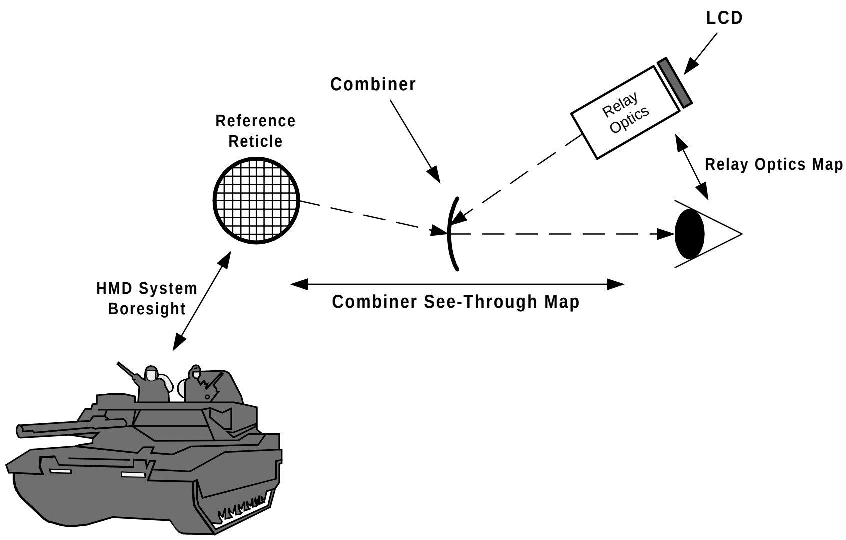

Figure 12 – B-HMD Optical Characterization Process

The process for characterizing B-HMD was:

1. Reference reticle points were measured directly and through the combiner to obtain the combiner see-through distortion map.
2. Locations on the combiner corresponding to illuminated pixel locations on the LCD were measured to obtain the relay optics distortion map.
3. A 6^{th} order polynomial bi-variate regression fit was performed on the combiner see-through data with the reference reticle coordinates as dependant variables and the combiner coordinates as independent variables.
4. A 6^{th} order polynomial was evaluated using the coefficients obtained in step 3 and the azimuth and elevation of the combiner coordinates obtained from the relay optics characterization. This step yielded a map relating LCD pixels to reference reticle coordinates.
5. The reference reticle coordinates were transformed to the "system" LOS using the coordinate transform and the System '*YPR*'.
6. The transformed coordinates were converted to input video pixels. This step depends upon the input video source characteristics.

The last step produced a "reverse" pixel map relating LCD pixels to input video pixels. This map was used in the final process for generating the distortion coefficients of the B-HMD, using a software model of a specialized IC that pre-distorts video for this system.

3.10 HMD testing

Testing a HMD uses many of the processes and algorithms involved in characterization. With the exception of registration testing, the generalized process flow can be stated as follows:

1. Using the distortion characterization coefficients, generate a pre-distorted test pattern from a desired input pattern (crosshatch, boxes, crosses, lines, etc.).
2. Transform the original undistorted test pattern coordinates to combiner or visor locations using the see-through characterization data.
3. Display the pre-distorted pattern from step 1on the HMD.

4. Perform a “soft” boresight to find the yaw, pitch, and roll of the image plane.
5. Transform the test pattern coordinate locations from step 2 to the optical bench reference frame using the coordinate transform and the measured yaw, pitch, and roll.
6. Measure the actual coordinates, line width, luminance etc., for the expected points.

Testing registration or “real” world overlay, involves the following generalized steps:

1. Measure external reticle locations directly, without a combiner or visor.
2. Transform the points to the combiner or visor using the see-through distortion characterization data.
3. Generate a pre-distorted pattern on the display using the coordinate locations obtained from step 1 and the end-to-end characterization coefficients.
4. Measure the generated points off the combiner or visor and compare them with the predicted combiner points from step 2.

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4. DATA FROM HMD PROGRAMS AT KAISER ELECTRONICS

Using an automated optical bench allowed M-HMD to make its initial deliveries on time and provided primary display accuracies and consistencies exceeding those of previous HMD programs at Kaiser Electronics. The M-HMD display registration accuracy has consistently been better than its requirement of 3 milliradians (RMS) maximum. The 1σ registration accuracy is 1.6 milliradians. Characterization and test time have been significantly reduced. Table 1 compares typical testing times for the automated bench with previously used methods.

Table 1 – Comparison of Test Times

Test	Number of Measured Points (M-HMD)	Test Time using Automated Bench	Previous Test Times (STD Test Equipment)
Relay Optics Characterization	225	55 min.	113 min. *
CRT Characterization	~225	55 min.	113 min. *
Visor Characterization	225 (x2)	40 min.	226 min. *
Line Width	5	7 min.**	10 min.
Registration	50	20 min.	45 min.

* Based upon 30 seconds/point, excluding setup time
** Semi-Automated

The B-HMD is nearing the first build of deliverable hardware and therefore, no actual data exists for comparison. However, the current accuracy analysis shows that registration will be significantly better than the 3 mr maximum requirement.

5. SUMMARY AND CONCLUSIONS

Using an automated optical bench to characterize and test HMDs provides measurable improvements in accuracy, repeatability, and throughput. A robust HMD testing system, adaptable to varied designs can be developed using COTS hardware and software, with judicious use of unique or proprietary interfaces and specialized tooling. Characterization is an important element in the process of delivering a quality HMD and can be facilitated using reusable software modules with careful attention to coordinate transformations. Further throughput improvements are possible through code/algorithm optimization and the development of optical benches with a wider staring field of view.