Stereo Camera and Stereo X-Ray Devices: Comparison of Biostereometric Measurements

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ABSTRACT: The Craniofacial Research Instrumentation Laboratory at the University of California, San Francisco, has developed instrumentation and software for the acquisition and analysis of stereo x-rays and photographs. Tests were performed in order to investigate the accuracy of the stereo coordinates obtained from each system. Stereo photographs and x-rays were taken of a targeted human skull and the X, Y, and Z coordinates of the targets were computed. Target coordinates had also previously been determined by direct survey. Comparisons were made among the various coordinate systems. Tests indicate that both systems operate at a satisfactory level of accuracy for craniofacial mapping.

INTRODUCTION

THE CRANIOFACIAL RESEARCH INSTRUMENTATION LABORATORY (CRIL) at the University of California, San Francisco, has developed a system for analyzing three-dimensional changes in craniofacial morphology using stereo cameras and x-ray devices. The system was developed under the guidance of Dr. S. Baumrind of the CRIL and in conjunction with the Photogrammetry Group of the Department of Civil Engineering at the University of California, Berkeley. The main objectives have been to develop imaging instrumentation that is rugged and simple to operate, and data acquisition and analysis software systems that are flexible and user-oriented.

The camera and x-ray hardware and data analysis software have been described in Baumrind *et al.* (1982) and Curry *et al.* (1982). The systems are now operational and in use at the University of California Medical Center in San Francisco. In this paper, we report on the initial practical tests of system performance. These tests were performed using a dried specimen skull with a number of small radiopaque targets attached. Both stereo photographs and stereo x-rays were taken, and the computed three-dimensional coordinates were compared to previously established values for the points.

A major focus of the CRIL system development has been the integration of craniofacial coordinate data from a number of sources, including facial and intra-oral photographs, study cast photographs, and cranial x-rays (Baumrind, 1975). Each biological "landmark" is located on the data source upon which it can be identified with the least ambiguity. For example, details of a single tooth are identified on study cast photography, facial contours and soft tissue on facial photographs, and underlying bony structures on x-rays.

In order to compile a composite coordinate data base, in a single frame of reference, common points must be made available from each object space. The various coordinate systems are merged using a seven parameter least-squares fit. The integration of data is in fact one of the most difficult aspects of our work, as unambiguous reference points may not always be available. Baumrind (1975) describes in detail the methods being used to provide such reference points. Clinical tests employing these methods are presently being performed by CRIL.

In order to evaluate the merging of data from the various camera and x-ray imaging devices, it is necessary to evaluate the systems from a photogrammetric standpoint. Errors in the three-dimensional coordinates due to film distortion, lens distortion, calibration errors, and digitizing errors need to be isolated from those due to difficulties in point location and identification. In a clinical setting, some points of interest may be discrete metallic implants, while others may be more subjectively defined anatomical landmarks. In this study, well-defined targets were placed on the specimen skull to reduce errors in point location. Although errors due to point location are still present using the discrete

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targets, they are of a lower order of magnitude than those present with "fuzzy" anatomical landmarks.

The targets were also sufficiently well separated such that there were no difficulties in target identification and numbering. Especially in the case of stereo x-rays, where the entire three-dimensional object is imaged in a single overlaid plane due to the penetration of the x-rays, potential confusion of target points is not a trivial problem. For example, two targets located on opposite sides of the skull, but both along the principal ray of the x-ray emitter, will be imaged in the same location on the film. Techniques are presently being developed to reduce such identification problems.

DATA ACQUISITION DEVICES

STEREOMETRIC CAMERA SYSTEM

The stereometric camera used in this study (Figure 1) was calibrated using a standardized calibration procedure described in Curry (1981). A flat aluminum plate with an array of well-defined control points is positioned parallel to the film plane with auto-reflection techniques. The plate is then displaced parallel to itself a precisely measured distance while two exposures are taken, thus creating a three-dimensional test field. The calibration routine provides calibrated principal points, principal distances, and lens distortion parameters for both lenses in the camera, as well as the base between the two. Because the two lenses are maintained at a fixed base of 111.61 mm, and in a known and rigid orientation to one another, there is no need for control in the object space. The average base/distance ratio is approximately 1:6.

The camera uses 70-mm roll film, held against an optical glass surface with a pressure plate. The glass image plane has an array of 16 fiducial marks etched on each lateral image surface. The lenses have focal lengths of approximately 80 mm, yielding a photographic scale of approximately 1:8. An optical rangefinder is mounted on the camera to aid in positioning the subject, and an electronic flash is used for illumination. Standard film processing techniques are employed, and either negatives or prints can be digitized. In addition to the stereo photographs used for quantitative analysis, a fixed stereo pair can also be prepared for qualitative viewing (Figure 2). It is hoped that in the future a standard set of stereo pairs will be included as a part of the patient's chart. The photos could be digitized at a later date for further quantitative data analysis, or used subjectively to judge the treatment progress and effects.

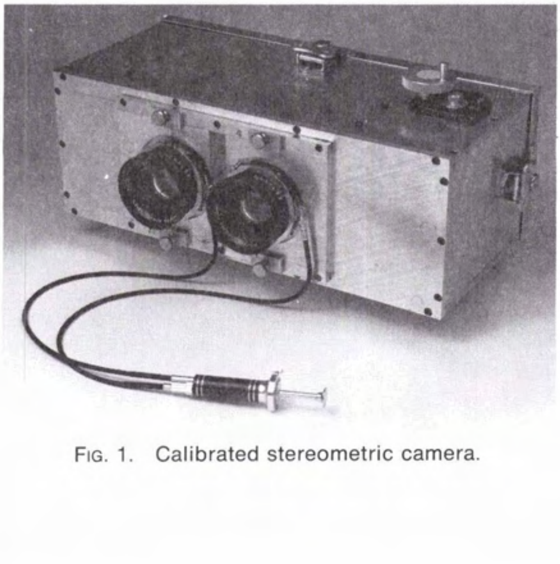

FIG. 1. Calibrated stereometric camera.

STEREO X-RAY SYSTEM

Stereo x-rays were exposed with a dedicated coplanar craniofacial x-ray system (Figure 3) located at the University of California Medical Center. It was calibrated using a combination of analytical and physical mensuration (Curry, 1984). The paired x-ray tubes have 0.3-mm focal spots and are located 60 inches (1524 mm) from the mid-sagittal plane of the subject. This is the plane that divides the skull into symmetric left and right halves. The right and left tubes have principal distances of 1704 mm and 1684 mm, respectively; a base of 435 mm; and a base distance ratio of approximately 1:4.

A spring loaded cassette changer is used to change films between exposures from the centered and offset tubes. There is an elapsed time of 1 to 2 seconds between exposures. Human subject movement is constrained by a headholder, and studies are presently being performed to evaluate the effects of any remaining subject movement on the final coordinates. Subject movement is not a consideration in the tests performed here due to the nature of the test object.

All images are exposed with rare earth screens on standard 8-inch by 10-inch (203.2-mm by 254.0-mm) x-ray films. A fiducial array consisting of four small lead spheres in the plate holding the film cassettes is exposed on each film. The fiducial marks are used in subsequent processing to control film distortions and to align the images. Various studies (i.e., Veress and Lippert, 1977) have examined the effects of x-ray film distortion and of the finite size of the x-ray focal spots on computed coordinate values. We reduce the effects of film distortions by transforming the image coordinates into the coordinate system of the fiducial array with a four parameter transformation. Errors due to the size of the focal spot are ignored.

Figure 4 consists of a sample stereopair from this system. Note the concentric rings in the centered film, and the amount by which they are displaced in the offset member of the pair. They are a part of a mechanical headholder, and are a useful illustration of the amount of image displacement between the two films.

FIG. 2. Sample stereopair from camera.

DIGITIZING AND PROCESSING SYSTEM

All data were digitized and processed using an interactive package developed by CRIL. The software, written in FORTRAN 77, runs on a VAX 11-750 computer under the UNIX operating system. Digitizing is performed online with a Kern MK2 Monocomparator interfaced to a menu-driven digitizing program. Each image is digitized three times, and the files of digitized coordinates are then passed to an averaging and checking program. Because the fiducials are also digitized and included in each file, additional digitizings of the same frame can be added at a later time and transformed to the system of fiducial coordinates. This allows for error correction and the addition of new points.

The averaged coordinates are passed to a general stereo computation program. The program determines which camera or x-ray device was used for image acquisition and refines the image coordinates appropriately. Digitized coordinate values are fit to the calibrated fiducial values using a four parameter transformation. All coordinates are then transformed to a principal point coordinate system and, in the case of the camera, corrected for lens distortions. The calibrated principal distance of the device is utilized in subsequent computations. Three-dimensional coordinates are computed from the least-squares intersection of conjugate rays, and the residual parallaxes are reported.

TEST PROCEDURES

TEST FIELD

In order to test the performance of the stereo camera and x-ray imaging devices, a test object of

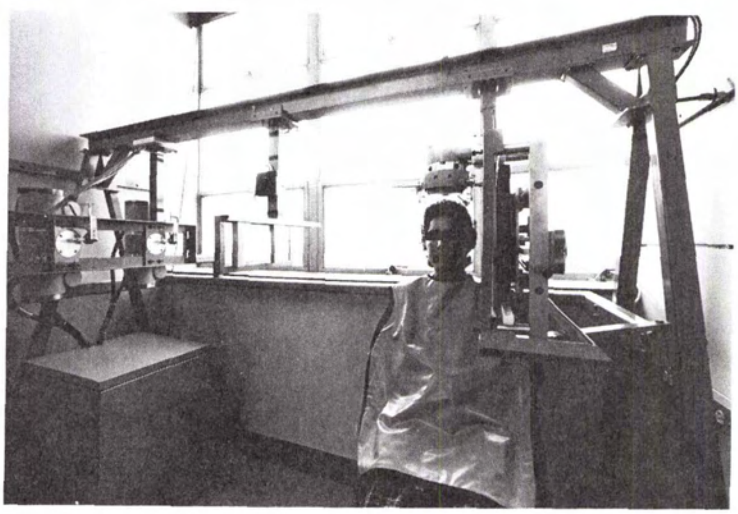

FIG. 3. Calibrated coplanar craniofacial x-ray system.

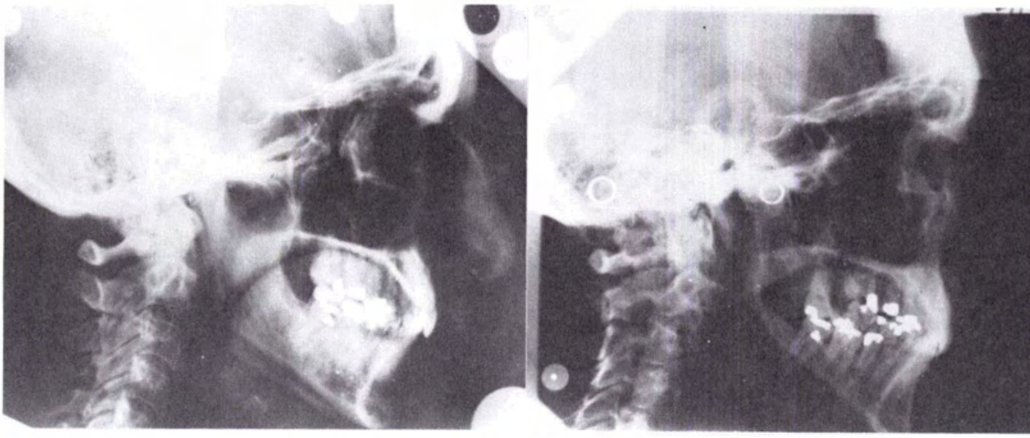

FIG. 4. Sample stereopair from x-ray system.

known dimensions was required. It needed to approximate in shape and size the objects that are being clinically examined, and it required well defined points that would be visible on both x-rays and photographs. We utilized a dried human skull with 13 small lead spheres (0.4-mm diameter) attached to its exterior (Figure 5). The dried skull produces a slightly sharper image on the x-ray than would a living subject, and the lead spheres are more readily digitized than "soft" anatomic points would be. However, as mentioned earlier, this sort of test field serves well for the determination of system performance. The question of errors in point location and identification are being studied in clinical trials.

Ideally, we would have preferred to compare the computed three-dimensional coordinates to those produced by direct measurement with a three-dimensional probe. However, because such a device was not available, we decided to determine the skull coordinates by direct surveying techniques, and use those as the datum for further comparisons. In order to establish some check on the surveyed coordinates themselves, direct distance measurements were made with calipers and compared to distances computed from the survey-derived coordinates.

The coordinates of the 13 test targest were therefore initially determined by direct survey. Three Wild T-2 theodolites and one Kern DKM 2 (least count, one arc second) were set up at the corners of a quadrilateral measuring approximately 3 metres by 1.5 metres. The X, Y, and Z coordinates of the four stations were determined by observing horizontal directions, horizontal distances, and vertical angles to all of the other stations (Figure 6). Horizontal directions were measured by initially sighting to the center point of the facing theodolite telescope with the telescope leveled. Precise alignment was performed by focusing both instruments on infinity and sighting one pair of cross-hairs on the other. Vertical angles were observed by matching the horizontal cross-hairs of the two theodolites, using a collimation technique described by Kissam (1962). Distances between stations were measured with a microrule on a scribed aluminum rod, and were then reduced to the horizontal.

The approximate quadrilateral coordinates were

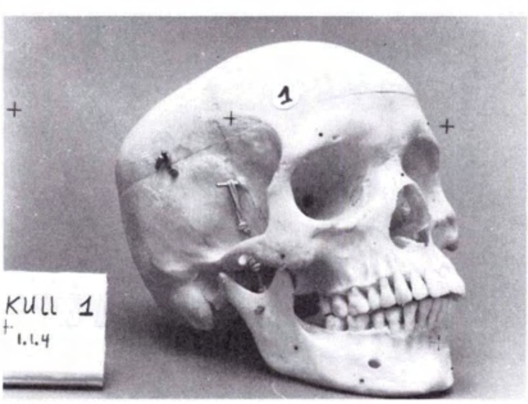

FIG. 5. Skull used for system testing.

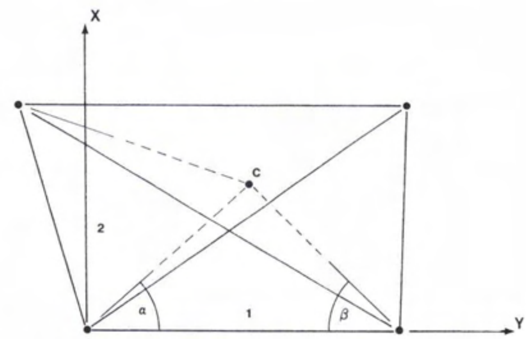

FIG. 6. Quadrilateral for survey determination of skull coordinates.

computed, and the approximate coordinates and all horizontal observations were used as input to a combined triangulation-trilateration least-squares adjustment. Measured distances were weighted more heavily than the angles, due to the short sight distances. From the adjusted measurements, it was determined that the directions had a standard deviation of 6 arc seconds and the distances a standard deviation of 0.1 mm. The combined adjustment resulted in estimated propagated standard deviations of 0.07 mm in X and 0.07 mm in Y for the adjusted station coordinates. The Z coordinates of the theodolite stations were determined by multiple direct and reversed sightings to a steel scale mounted on an adjacent wall. The reduced values for the Z coordinates had a standard deviation of 0.01 mm.

Once the theodolite station coordinates were known, the skull target coordinates were determined by observing horizontal directions and zenith angles from the two stations with the best view of each point. The coordinates were computed using the following standard equations:

$$Y_c = \frac{X_b - X_d + Y_d \cot\alpha + Y_b \cot\beta}{\cot\alpha + \cot\beta}$$
$$X_c = \frac{Y_d - Y_b + X_d \cot\alpha + X_b \cot\beta}{\cot\alpha + \cot\beta} \quad (1)$$

The angles α and β were derived from the measured directions. Note that all coordinates were computed in a left-handed coordinate system in order to conform to craniofacial measurement convention. The above equations were applied to either triangle 1 or triangle 2 in Figure 6, depending on which had the better view of the target.

The errors in quadrilateral station coordinates were propagated to determine estimated standard deviations for the skull targets. The variance matrix for X and Y was derived from

$$\mathbf{\Sigma}_{XY} = \mathbf{J}_{XY}\,\mathbf{\Sigma}_{obs}\,\mathbf{J}_{XY}^{T} \quad (2)$$

where $\mathbf{J}_{XY}$ is the Jacobian representing partial derivatives of X_c and Y_c with respect to X_b, Y_b, X_d, Y_d, α, and β in Equation 1 and $\mathbf{\Sigma}_{obs}$ is the variance matrix for coordinates of the stations occupied (X and Y assumed uncorrelated) and the measured angles α and β.

For the worst case in triangle 1,

$$\sigma_X = \pm 0.08 \text{ mm}$$
$$\sigma_Y = \pm 0.13 \text{ mm}$$

For the worst case in triangle 2,

$$\sigma_X = \pm 0.14 \text{ mm}$$
$$\sigma_Y = \pm 0.19 \text{ mm}$$

The Z coordinates were computed using the formula

$$Z = \sqrt{(X^2 + Y^2)}\cot\zeta + Z_s \quad (3)$$

where X = X coordinate from above,
Y = Y coordinate from above,
ζ = observed zenith angle, and
Z_s = station Z coordinate

The estimated standard deviations in Z were determined from

$$\mathbf{\Sigma}_Z = \mathbf{J}_Z\,\mathbf{\Sigma}_{XY\zeta Z_s}\,\mathbf{J}_Z^{T} \quad (4)$$

The average estimated standard deviation in Z was 0.24 mm.

The surveyed skull coordinates were checked by computing the distances between various pairs of points and also physically measuring the distances with dividers and a micro rule. These measured and computed distances are shown in Table 1. The discrepancies were generally less than 0.2 mm, except for those distances involving Target 9. It was then determined that Target 9 had not been properly attached to the skull, and had moved at some point during the measuring procedure. It was therefore excluded from subsequent tests.

Test Imagery

The skull was photographed and x-rayed using the calibrated devices described in earlier. Three pairs

Table 1. Comparison of Computed Distances

SAMPLE DISTANCE COMPARISON							
Distance	Measured (mm)	Surveyed	Diff.	Photo	Diff.	X-Ray	Diff.
11-12	57.40	57.43	0.03	57.23	−0.17	57.20	−0.20
1-5	49.65	49.42	−0.23	49.79	0.14	49.57	−0.08
6-2	46.48	46.32	−0.16	46.53	0.05	46.51	0.03
10-12	88.90	88.93	0.03	89.01	0.11	88.67	−0.23
6-11	60.52	60.35	−0.17	60.47	−0.05	60.48	−0.04
3-4	11.07	11.27	0.20	11.34	0.27	11.39	0.32
13-3	104.90	105.08	0.18	105.20	0.30	105.10	0.20
10-4	50.80	50.79	−0.01	50.91	0.11	50.97	0.17
12-8	49.50	49.64	0.14	49.51	0.01	49.64	0.14
RMS			0.15		0.16		0.18

of photographs of the skull were taken so that each target appeared on at least one stereo pair. Two pairs of stereo x-rays were taken, with each target appearing on both x-rays. Each image point was digitized three times on each x-ray and photograph, and the averaged values were then processed through the CRIL package. Separate files of three-dimensional coordinates were generated for each stereo pair and stored for analysis.

COMPARISON OF COORDINATES

Table 1 shows a comparison among sample distances computed from the derived three-dimensional coordinates, and those measured directly on the skull with dividers and a microrule. Although the direct measurements are considered as the standard in this table, they are also subject to measurement error. However, they do indicate that the surveyed coordinates are accuate enough to use in the three-dimensional coordinate merging tests. The size of the sample tested was restricted to those distances which could be effectively measured with calipers and a microrule. Thus, the set tested is necessarily small.

The distance measurements in Table 1 indicate an acceptable level of system performance for craniofacial mapping. On the average, computed distances compare with the measured ones to around 0.2 mm, with root-mean-square (RMS) errors of 0.15 mm, 0.16 mm, and 0.18 mm for surveyed, photographic, and x-ray measurements, respectively.

The computed X, Y, and Z coordinates for the twelve check points from the skull x-rays and photographs were then compared to the surveyed coordinates of the corresponding points. Note that, although the surveyed coordinates are considered errorless and fixed in this test, they are in fact also subject to measurement errors. However, as noted earlier, their standard deviations were known to be slightly less than 0.2 mm, and within acceptable limits for testing the photogrammetric accuracy of the systems.

Table 2 shows a comparison of the RMS errors in discrepancies of coordinates obtained by the fitting of all three-dimensional coordinate data sets onto the surveyed coordinates. Also shown in Table 2 are reference variances for each adjustment and the respective scale factors. The fits are all comparable, both in terms of RMS errors and scale factors. This is important to our work, where we will be statistically testing fitted data sets from these devices. All adjustments were done with a seven parameter least-squares fit. In each case, all common points were used as input to the program. After the data had been rotated, translated, and scaled to the best fit with the surveyed coordinates, residuals were reported for each point, and the reference variance of the adjustment was then computed.

Assuming that the adjustments are all independent, these reference variances can be statistically tested. We are particularly interested in whether the reference variances are homogeneous, indicating that the coordinate data sets are of comparable accuracies. Bartlett's test allows the homogeneity of the variances to be tested (Hamilton, 1965). If the sample variances are $\mathbf{S}_1, \mathbf{S}_2, \ldots, \mathbf{S}_n$ with $V_1, V_2, \ldots, V_n$ degrees of freedom, then

$$\mathbf{S}^2 = \frac{\Sigma V_i \mathbf{S}_i^2}{\Sigma V_i} = \text{the pooled variance estimate.}$$

The statistic

$$M = (\Sigma V_i)\log\mathbf{S}^2 - \Sigma V_i \log\mathbf{S}_i^2$$

can be computed and, if all the V's are greater than 5, can be approximated by

$$X^2_{n-1}$$

In the tests presented here, V (degrees of freedom) ranged from 20 to 30.

TABLE 2. COMPARISON OF MERGES

	FITTED COORDINATE COMPARISON Fitted to Surveyed Coordinates					
Set	Points	RMSE X	RMSE Y	RMSE Z	σ_0	Scale
Photo Pair 1	10	0.17	0.22	0.05	0.178	1.0001
Photo Pair 2	12	0.22	0.27	0.09	0.162	0.9995
Photo Pair 3	7	0.16	0.19	0.08	0.171	0.9960
X-Ray Pair 1	12	0.15	0.17	0.07	0.146	1.0001
X-Ray Pair 2	12	0.16	0.16	0.11	0.153	1.0011

In this case, the null hypothesis

$$H_0 : \mathbf{S}_1^2 = \mathbf{S}_2^2 = \cdots \mathbf{S}_n^2$$

can be rejected only if

$$M > X^2_{1-a,n-1}.$$

M in this case is computed to be 0.210. From tables, at the 0.01 level of significance, $X = 13.30$, and the null hypothesis is accepted. The adjustments can be said to have homogeneous reference variances.

CONCLUSIONS

The main objectives of this investigation were to determine the levels of accuracy that could be obtained from the CRIL stereometric camera and x-ray system under normal conditions. No special procedures were employed in image acquisition, film processing, or data processing. Both systems produce coordinate sets of comparable accuracy, where the homogeneity of the results was verified by Bartlett's test. Thus, we can fit the three-dimensional coordinates from x-ray and photographic images with some confidence. Distance and coordinate errors are generally less than 0.2 mm, which is more than adequate for craniofacial mapping.

ACKNOWLEDGMENTS

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