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Aortic Heart Valve Geometry*

The design and manufacture of the prosthetic valve is being undertaken on the basis (in part) of the geometry and dimensions provided photogrammetrically.

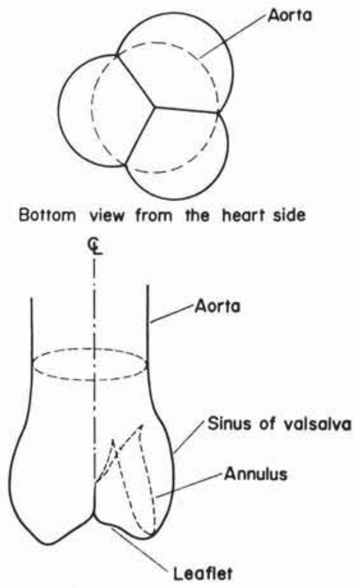

FIG. 1. Aortic Valve configuration. (After Gould, *et al.*[4])

INTRODUCTION

THE AORTIC VALVE is a one-way check valve between the left ventricle of the heart and the aortic artery, as sketched in Figure 1. The valve is composed of three approximately crescent-shaped leaflets. As the heart pumps, the tri-leaflet aortic valve opens and closes, thus allowing the blood to flow from the left ventricle during the ejection (systolic) stage, and preventing fresh blood from backing up into the left ventricle in the filling (diastolic) stage. During the systolic stage, the three leaflets fold back toward the wall of the aorta, thus opening the valve. In the diastolic stage, the leaflets come together, thus closing the valve. If the natural valve is damaged by disease, such as rheumatic fever, or injury, it does not close properly, thus decreasing the heart's efficiency. To rectify this situation, the damaged aortic heart valve is replaced by a synthetic valve.

Prosthetic heart valves of various types and designs have been in use for some time. Tens of thousands of people have had their aortic heart valve replaced. Synthetic valves used so far require the continual use of anticoagulants which can have undesirable side effects.

Since some four years ago, a multidisciplinary research team headed by R. E. Clark, M. D., of the Division of Car-

ABSTRACT: *The work reported on in this paper is a part of a cooperative effort between the Department of Civil Engineering of the University of Illinois at Urbana-Champaign and the Division of Cardiothoracic Surgery and the Department of Civil and Environmental Engineering of Washington University, St. Louis, Missouri, on the development of a tri-leaflet prosthetic heart valve. The photogrammetric studies were conducted on silicone rubber molds. Data acquisition and data reduction phases result in the report of accuracy aspects of the project and the various outputs (digital models, profiles, contour maps, etc.).*

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diothoracic Surgery, Washington University, St. Louis, has been working on the development of a new prosthetic tri-leaflet aortic heart valve which is an improvement over valves used currently. This research team is composed of professionals from a number of disciplines including cardiothoracic surgery, structural engineering, fluid mechanics materials, computer science and photogrammetry.

The proposed prosthetic valve will be a central flow device, just as the actual human valve, rather than the current central occluding devices which have less than satisfactory hydrodynamics with resultant blood degradation and thromboembolic phenomena.

An overview of the various studies involved in the total project were summarized by Clark, *et al.*:[3] "A complete multi-phasic study has been performed which involved (1) the careful definition of the normal anatomy of leaflets, including the surface characteristics, thickness variations, and composite nature of the internal structure; (2) uniaxial stress-strain data on leaflet tissue discerned the anisotropic and nonlinear behavior in the very low stress region; (3) a numerical-graphic analysis of the opening characteristics of the aortic valve detailed the magnitude and relations of bending, shear, and loading stresses; (4) a detailed analysis of the distribution of in-plane stresses was made through the use of close-range stereophotogrammetry which defined the asymmetric shell surfaces in global coordinates; (5) a computer-based finite element method of analysis was used to obtain the principal stress resultants over a physiologic pressure range; (6) ultra-pure polyester resin was made and extruded into $10\mu m$ fibers and woven into a multilayered fabric to yield variation in thickness, mechanical behavior and surface characteristics superior to previous devices. The rationale and durability aspects of this project will be discussed."

An accurate assessment of the geometry of human aortic heart valves is necessary to develop the configuration of the synthetic heart valve and determine the necessary strength and elasticity for the synthetic fabric, which is of a gauze-like structure, to withstand the pressures to which the prosthetic valve will be subjected in the human body.

Because the maximum stress on the heart valve is induced when the valve is closed and subject to diastolic pressure, it was decided to determine the valve geometry during diastole. Because the actual valves could not be measured, molds of freshly excised human aortic valves were used instead. A typical heart valve mold is shown in Figure 2. The molds were formed by pouring a silicon rubber material into the excised aorta, thus causing the valve to close. In this way, the molds accurately represented the topography of the valves. For each valve studied, a series of molds were made under varied pressures (20 mm Hg, 40, 60, 80, 100 and 120 mm Hg), to represent the valve's surface under different pressures. This was necessary for the stress-strain analysis.

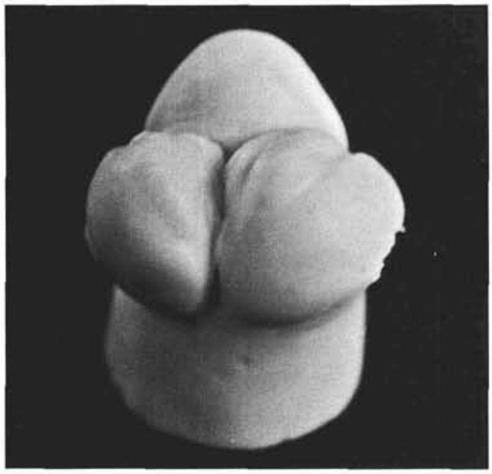

FIG. 2. A typical heart valve mold.

The size of the molds (10-30 mm in diameter) and the complexity of the surfaces precluded the use of direct measurements to determine the geometry of the molds. Hence photogrammetry was chosen as a vehicle for the assessment of the topography of the molds, through the following outputs: (a) digital models, (b) surface profiles, (c) contour maps. An accuracy (maximum standard deviation) of at most ± 0.3 mm in the spatial coordinates of surface points was considered adequate for the purposes in which these outputs were to be used.

Description of the Photogrammetric System Used

Preparatory Steps

Object-Space Control. To provide basic object-space control, a 3 × 3 × 3-inches control object composed of three mutually perpendicular and precision-machined aluminum plates of ⅛-inch thickness (Figure 3) was used. A 6 × 6 orthogonal matrix of 36 tiny holes of some 0.02-inch diameter were precision drilled in the surface of each of the three planes, filled with a mixture of glue and

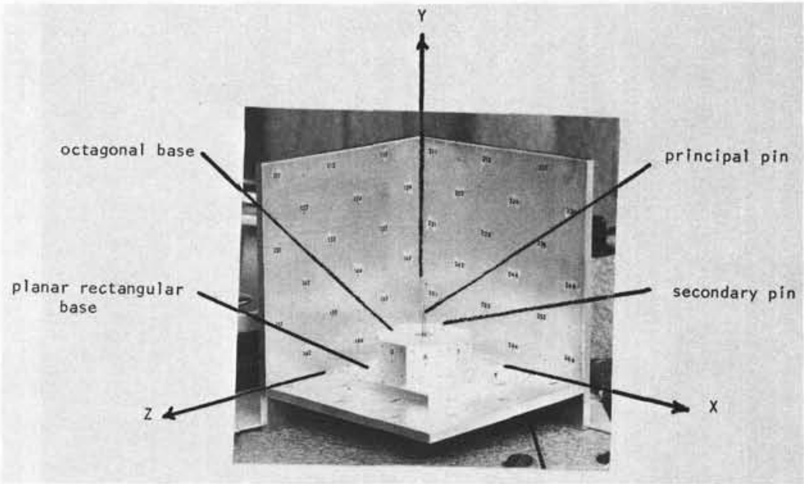

FIG. 3. Object-space control with object-space X, Y, Z coordinate axes.

dye. The three lines of intersection of the three planes were adopted as object-space coordinates (X,Y,Z) axes, with their common intersection point as origin. The increments in X,Y and Z for all points drilled on the surfaces of the three mutually perpendicular planes were 0.5 ± 0.005 inch. The thusly obtained spatial coordinates of the control points were used as a basis for the spatial transformation outlined in a subsequent section.

The flatness of the three mutually perpendicular planes was reported as being well within ± 0.01 mm. No special tests were conducted to verify this tolerance, in view of the relatively relaxed accuracy requirements of the project. The orthogonality of the three planes was controlled by a series of tiny holes drilled parallel to the X, Y and Z axes of the control object. Every possible care was taken in assembling the three mutually orthogonal aluminum plates, but in view of the relatively liberal accuracy requirements of the project, no special tests were conducted to verify the orthogonality of the planes, beyond the checks conducted in the machine shop. As will be explained later, a test was conducted to assess the overall absolute accuracy of the entire process used in this project, and the results obtained (reflecting the errors associated with the object-space control as well as the errors involved in the photogrammetric process) were well within the specified accuracy requirements.

The molds were affixed to an octagonal base rigidly mounted on a planar rectangular base which could be rotated around an axis (principal pin in Figure 3). The planar base could be held fixed in any desired orientation in the X-Z plane. Tiny holes, similar to the ones drilled in the surface of the three mutually perpendicular planes, were drilled in the surfaces of the octagonal base and the planar rectangular base.

The molds were held in position on the top of the octagonal base using the two pins visible in Figure 3. This arrangement enabled the rotation of the mold relative to the fixed control point system. The dots on the rotatable parts were used to correlate the stereopairs of the mold taken in various orientations, as explained later.

Surface Contrast. As mentioned earlier, the molds were formed of a silicone rubber material. Some molds were off-white and others were pastel blue in color, providing no surface contrast.

To provide the surface contrast necessary for the photogrammetric process, several approaches were tried; the approach deemed most suitable for this project consisted of inserting a dense network of tiny black ink dots on the surface of the molds. Even though randomly positioned dots would have fully satisfied the photogrammetric requirements, it was decided to place the dots along profiles (Figure 4) to facilitate the comparison of the results from one mold to another and to guide the instrument operator in the data reduction phase in systematically identifying and observing all visible image points.

In the early stages of the project, a Wild A7 autograph was used to locate the dots on the mold surface. Using a Rapidograph #00 pen mounted on the Z carriage of the A7 (Figure 5), tiny ink dots were painstakingly placed along profiles on the mold. Dots were also placed along identifiable boundaries on the

FIG. 4. A heart-valve mold with its surface processed, mounted in the control object.

FIG. 6. Placing dots on the mold's surface using a home-made device.

mold surface. The use of the A7 in this phase provided a unique vehicle for the assessment of the absolute accuracy of the total operational system.

To relieve the A7 from this operation, a simple device (Figure 6) was designed and manufactured at the University of Illinois. This device allows the positioning and orientation of the molds as desired, for placing dots on the mold's surface using a Rapidograph pen.

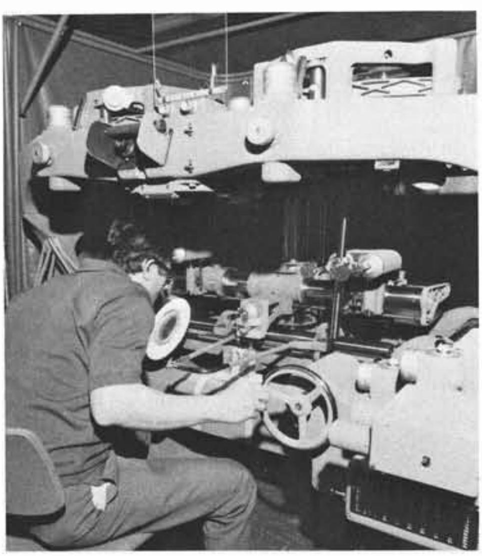

FIG. 5. Placing dots on the mold surface using a Wild A7 Autograph.

With the dots placed on the mold surface in profiles and along recognizable boundaries, a five-digit identification system was used to identify each dot. These digits identified the leaflet, the profile or boundary, and the point sequence in the profile or boundary.

DATA ACQUISITION

Because of the small size of the molds and the desirability to work with photographs of as large a scale as possible, it was deemed necessary to use a non-metric camera in view of the focusing flexibility of such cameras. Our group has accumulated considerable experience in the reduction of metric data from non-metric photography (e.g., References 2 and 5) and this was one of the factors that led to the decision to use a non-metric camera for data acquisition in this project.

A Hasselblad 500C camera, image format 55 × 55 mm, equipped with a Zeiss Planar 50 mm, *f*/4 wide-angle lens was used. Kodak Tri-X 70 mm film (ASA 400) was utilized.

Stereopairs of photographs were taken according to the Normal-Case of Photogrammetry, or approximately so, with the camera axes parallel and approximately perpendicular to the base. This was accomplished by keeping the camera stationary and moving the control object containing the heart valve mold after the first of the two photographs of the stereopair was taken.

The control object, with the mold mounted in it, was placed on one of the carriages of a Wild STK stereocomparator. The camera was positioned with its axis approximately per-

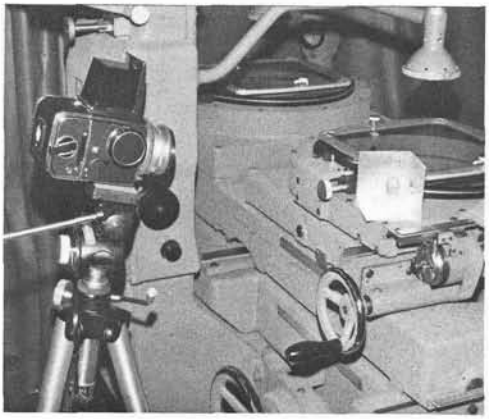

FIG. 7. Data-acquisition setup.

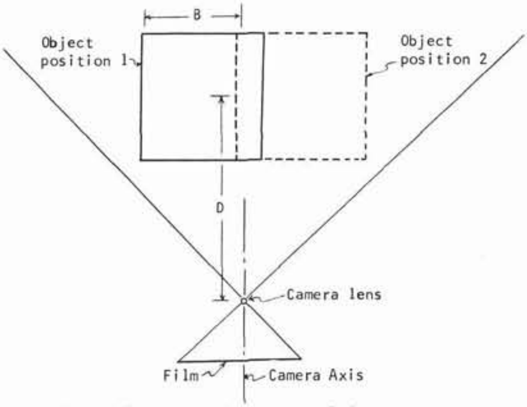

FIG. 8. Schematic diagram of data-acquisition setup.

pendicular to the direction of the X-translation of the stereocomparator, with a depression angle of some 20°-30°. The second photograph of each stereopair was taken after the STK carriage was translated in the X direction after the first photograph was taken. Figure 7 shows the data acquisition setup; Figure 8 gives a schematic diagram of the setup. Base-to-Distance *B:D* ratio was approximately 1:2. The displacement *B* of the object was precisely measured (difference between *X* readings of the stereocomparator's carriage) and used as input in data reduction.

In some of the tri-leaflet molds studied in the early stages of the project, only one of the three leaflets (leaflet *A*) was measured. The other two leaflets were carefully removed from the mold using a sharp knife, to enable the study of the coaption area of the leaflet of interest. In such applications, four oblique sideview stereopairs were taken (Figure 9). The rotatable base, on which the leaflet was mounted, was rotated some 90° between successive stereopairs to provide full stereocoverage of the entire leaflet.

In a few early molds, the geometry of the whole mold was studied. In such instances, seven stereopairs were involved, six oblique sideview stereopairs (Figure 10) and a topview stereopair. For the topview stereopair, the planar base of the control object was placed at approximately 45° to the *XY*, *YZ* and *XZ* planes (as illustrated in Figure 12).

For most molds, however, each of the three leaflets was studied as a separate unit and the

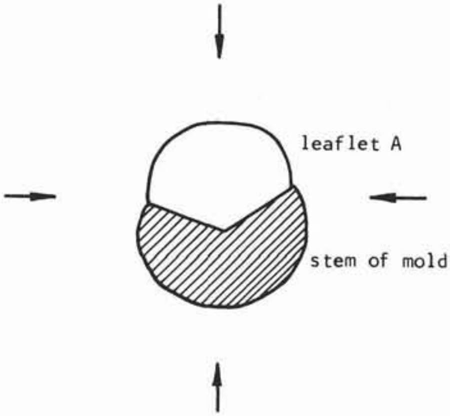

FIG. 9. Direction of the four oblique sideview stereopairs to study an individual leaflet (Leaflet *A*) of a tri-leaflet mold.

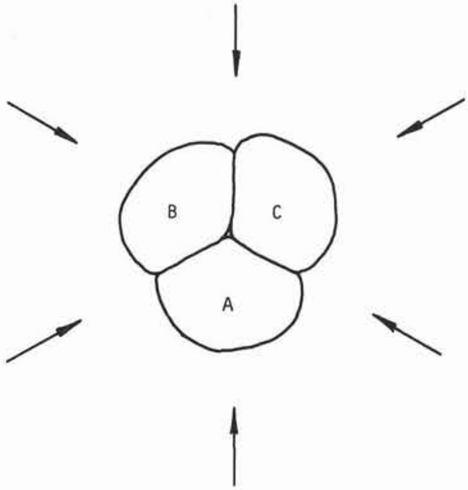

FIG. 10. Direction of the six oblique sideview stereopairs to study whole tri-leaflet molds in the early stages of the project.

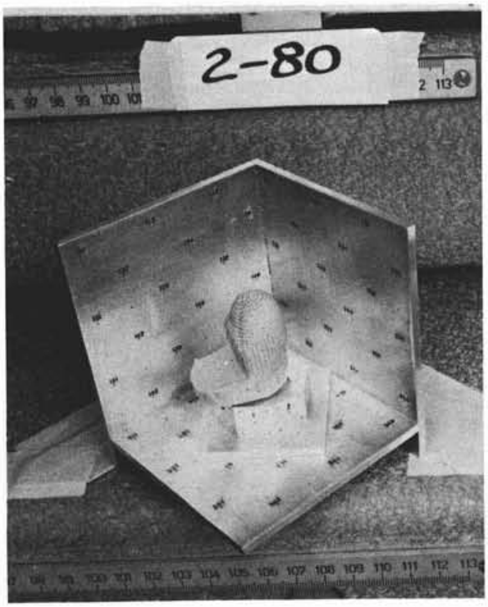

FIG. 11. A reproduction of a part of one of the photographs of one of the four oblique sideview stereopairs for Leaflet A of one of the molds.

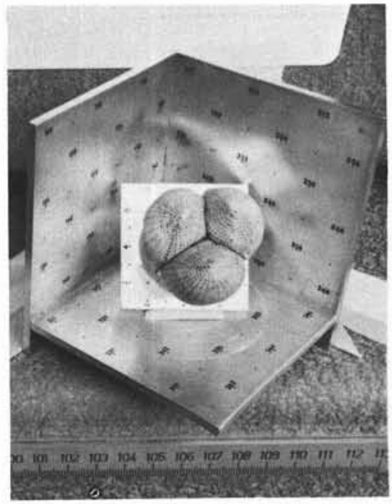

FIG. 12. A reproduction of a part one of the photographs of the topview stereopair of a tri-leaflet mold.

tri-leaflet mold was also studied as a whole. To accomplish this, the three leaflets were carefully separated from each other and their surfaces were processed as explained earlier. For each leaflet, four oblique sideview stereopairs were taken as outlined earlier and as shown in Figures 9 and 11. The three leaflets of each mold were then carefully reassembled and glued together, forming the tri-leaflet mold once again. A topview stereopair was then taken as explained earlier and as illustrated in Figure 12. Thirteen stereoviews were thus involved in the complete study of each mold.

The films were processed in the regular commercial fashion in a photolab. No special precautions were taken during or after processing. The original negatives were used in the phase of data reduction.

DATA REDUCTION

During the first year of the project, a Wild A7 autograph was available for use in this project. For the remaining duration of the project, a Wild STK stereocomparator was used for data reduction. With the A7, the semi-analytical approach was used. With the STK, the analytical approach was utilized.

In both instances, observations were made on the original negatives.

Semi-Analytical Reduction. An approximate principal point of each photo was determined as the intersection of the two diagonals of the photo format. A principal distance of 100 mm was used, resulting in an affine model in the A7. Relative orientation was accomplished using κ', κ'' and b'_z. The base B measured by the displacement of the STK carriage was introduced in the autograph. All visible images of control points and inserted surface dots were observed, three times each, and their model coordinates x, y, z recorded. At the same time, a plot of all points observed was obtained using the A7 plotting capability.

The relationship between object-space coordinates of any point and its observed model coordinates (in the A7 machine coordinate system) can be expressed through the following transformation equation:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} \lambda_x \cdot x \\ \lambda_y \cdot y \\ \lambda_z \cdot z \end{bmatrix} + \begin{bmatrix} m_{14} \\ m_{24} \\ m_{34} \end{bmatrix} \quad (1)$$

where X,Y,Z are object-space coordinates of a point, x,y,z are observed stereomodel coordinates of the same point, m_{11} through m_{34} are elements of rotations and translations of absolute orientation, and λ_x, λ_y, λ_z are scale factors, considering the affine nature of the model. Equation 1 can be rewritten as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} a_{14} \\ a_{24} \\ a_{34} \end{bmatrix} \quad (2)$$

where a_{11} through a_{34} are the parameters of transformation from observed stereomodel coordinates x,y,z into object-space coordinates X,Y,Z. Equation 2 involves 12 transformation parameters. Four control points are necessary for a unique solution of the 12 transformation unknowns. Using all the control points that were observed in a stereomodel, one obtained a strong least-squares solution for the transformation parameters. Through these 12 transformation parameters, the model coordinates of each observed point on the mold's surface were then transformed into the stereopair's object-space coordinate system, thus providing a partial digital model referred to that stereopair's object-space coordinate system. Further transformations were undertaken to obtain a complete digital model of each of the leaflets and of the mold, referred to a unique global coordinate system. These steps are discussed later inasmuch as they were performed in conjunction with both the semi-analytical and the analytical reductions.

Analytical Reduction. The Direct Linear Transformation (DLT) approach[1] was utilized to establish the relationship between the observed comparator coordinates and the object-space coordinates of the points. The following equations were used for this transformation. It should be noted that only the linear components of the film deformation and lens distortion are compensated for in the DLT equations used:

$$x = \frac{l_1X + l_2Y + l_3Z + l_4}{l_9X + l_{10}Y + l_{11}Z + 1}$$

$$y = \frac{l_5X + l_6Y + l_7Z + l_8}{l_9X + l_{10}Y + l_{11}Z + 1} \qquad (3)$$

where x,y are comparator coordinates of an image point, X,Y,Z are object-space coordinates of that point, l_1 through l_{11} are transformation parameters.

For each photograph, eleven transformation unknowns are involved. Using single prime (′) for the left photo of a stereopair and double prime (″) for the right photo, the following relationships were obtained for each point visible in the stereomodel:

$$(l'_9x' - l'_1)X + (l'_{10}x' - l'_2)Y + (l'_{11}x' - l'_3)Z + (x' - l'_4) = 0$$

$$(l'_9y' - l'_5)X + (l'_{10}y' - l'_6)Y + (l'_{11}y' - l'_7)Z + (y - l'_8) = 0$$

$$(l''_9x' - l''_1)X + (l''_{10}x'' - l''_2)Y + (l''_{11}x'' - {}''_3)Z + (x'' - l''_4) = 0$$

$$(l''_9y'' - l''_5)X + (l''_{10}y'' - l''_6)Y + (l''_{11}y'' - l''_7)Z + (y'' - l''_8) = 0 \qquad (4)$$

From these four equations the object-space coordinates X,Y,Z of the observed point were determined.

Further Transformations to Obtain Complete Digital Models of the Individual Leaflets and of the Molds. Because the orientation of the leaflet (to be studied as an independent unit) in the control object was different in each of the four stereopairs, the transformations outlined above produced a partial digital model of the leaflet from each stereopair. Each of these four partial models, however, was referred mathematically to a different X,Y,Z object-space coordinate system. To obtain the complete digital model of the leaflet, a further operation was necessary to combine the four partial digital models by referring them to a common coordinate system. A relationship similar to Equation 1 was used to accomplish this transformation:

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \begin{bmatrix} d_{14} \\ d_{24} \\ d_{34} \end{bmatrix} \qquad (5)$$

where X,Y,Z are object-space coordinates of a point referred to the object-space coordinate system of the partial digital model, X',Y',Z' are object-space coordinates of the same point, referred to the global object-space coordinate system of the total digital model, and d_{11} through d_{34} are transformation parameters.

With four partial digital models, the coordinate system of one of them was adopted for the total digital model, and the remaining three partial digital models were transformed into the global coordinate system chose. A simultaneous least-squares solution was performed. A total of 36 unknowns (transformation parameters), 12 for each of the three partial digital models, were involved in the solution. All common points observed were used in the solution, thus providing a favorable redundancy. This step provided a complete digital model for each of the leaflets, treated as an independent unit.

To obtain a total digital model of the reassembled tri-leaflet mold, the three complete digital models of the leaflets were transformed into the object-space coordinate system of the topview stereopair. A least-squares solution using an equation similar to Equation 2, incorporating all common points, was used. Because no points were common between the individual leaflets, no simultaneous solution was necessary in this phase.

It should be mentioned here that in the early stages of the project, a simple step-by-step solution similar to traversing in surveying, was using to assemble the four partial digital models of each leaflet into a complete digital model of the individual leaflet. Full details about this approach are given in Reference 6. The *simultaneous solution* described above was subsequently used in two-thirds of the molds studied in this project. Both approaches yielded essentially the same results and both were fully satisfactory, but the simultaneous solution required less operational time.

Accuracy Aspects

A test was conducted on one of the molds to assess the overall accuracy of the entire process used in this project. As each ink dot was inserted on the surface of the mold, its x,y,z coordinates (in the A7 machine coordinate system) were recorded. Thus *direct* spatial measurements of the mold points were obtained. After transforming these coordinates into the X,Y,Z coordinate system of the total digital model, the direct measurements were compared to the photogrammetrically deduced coordinates. Twenty-three randomly selected points yielded the following results:

Standard deviations: $\sigma_X = 0.10$ mm, $\sigma_Y = 0.06$ mm, $\sigma_Z = 0.05$ mm.
Median of differences: in $X = 0.08$ mm, in $Y = 0.02$ mm, in $Z = 0.02$ mm.

These figures, which reflect the errors associated with the control points as well as the errors involved in the photogrammetric process, indicated that the accuracy achieved was well within the level specified for the project (maximum standard deviation of at most ± 0.3 mm in the spatial coordinates of mold points).

Of interest also is a comparison between independent plots of a profile in one of the molds (mold 100 in Series 2) obtained from independent measurements made by two operators, each using stereoviews taken on different dates (Figure 13).

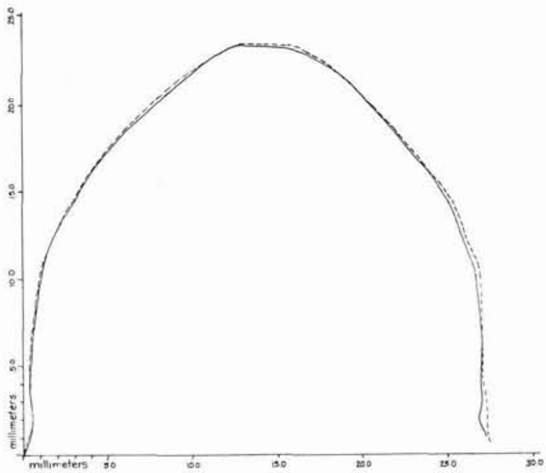

FIG. 13. Two independent plots of a profile of Mold 100 in Series 2, deduced from observations made by two operators each using stereoviews taken on different dates. The solid line represents photographs taken on October 9, 1972, and the dashed line on February 19, 1973.

Outputs

The photogrammetric outputs provided to the Structural Group were as follows:

- Digital models of individual leaflets and/or of the whole mold, as required,
- Sketch plans (Figure 14) used to aid the users of the photogrammetric outputs in locating the various points in the digital models.
- Profiles (Figure 15) were Cal-Comp produced on the basis of the spatial coordinates of the digital model.

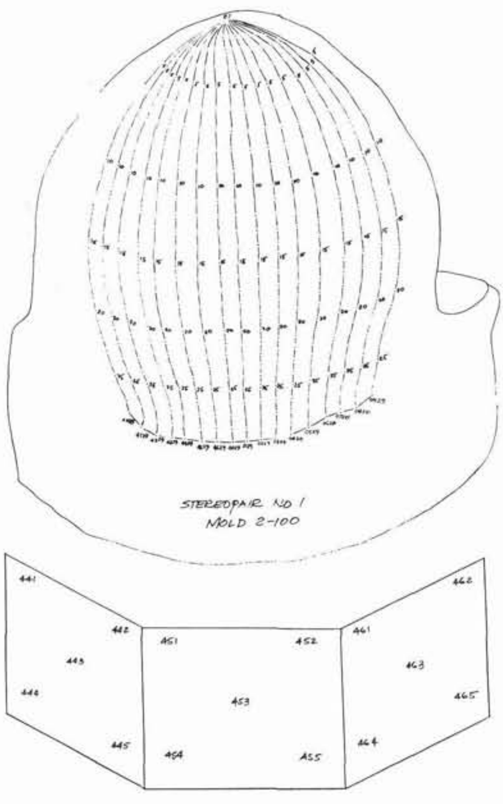

FIG. 14. Sketch plan of mold and octagonal base points observed in one of the sideview stereomodels of Leaflet A of Mold 100 in Series 2.

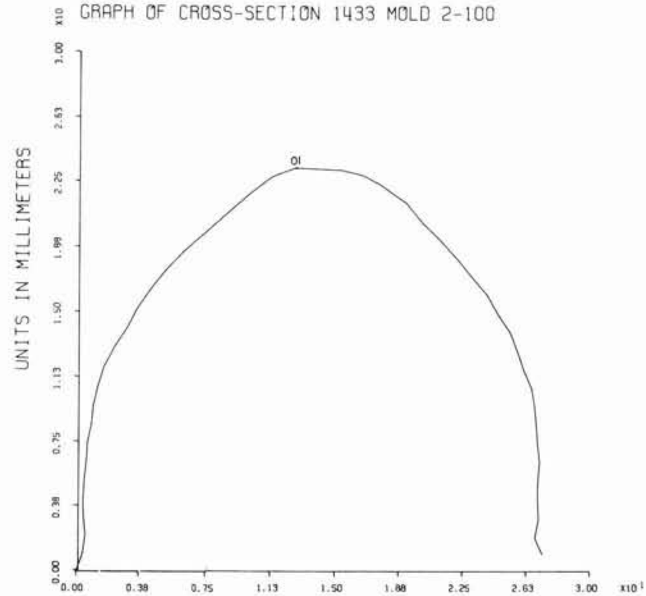

FIG. 15. A profile in Mold 100 in Series 2.

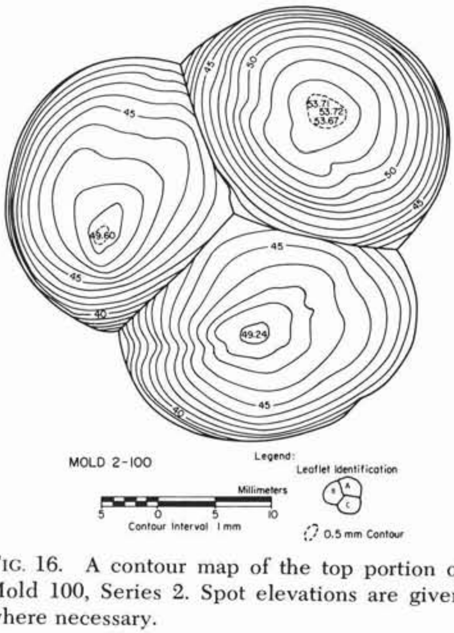

FIG. 16. A contour map of the top portion of Mold 100, Series 2. Spot elevations are given where necessary.

- Contour maps (Figure 16) were not produced for each mold, but were made upon request in a few instances. These maps were constructed on the basis of the spatial coordinates of the digital model.
- Dimensions of the coaption area: along each profile, spatial distances in the coaption area, as indicated in Figure 17, were deduced from the coordinates provided in the digital model.

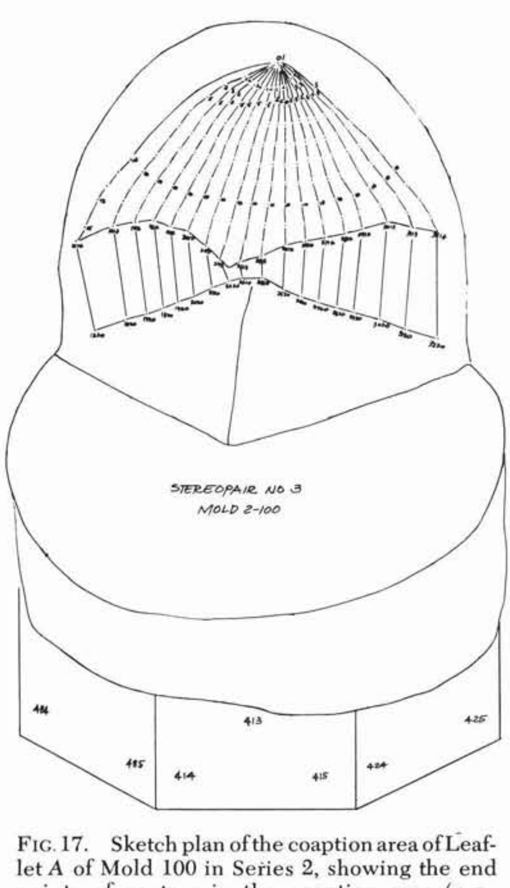

FIG. 17. Sketch plan of the coaption area of Leaflet A of Mold 100 in Series 2, showing the end points of vectors in the coaption area (e.g., 3214-3220, 1614-1620, 2213-2220, etc.)

Concluding Remarks

Based on the photogrammetric outputs provided for three series of molds (total of 18 molds), stress analysis was conducted by the structural group using a thin-shell finite element model. The design and manufacture of the prosthetic valve is being undertaken on the basis of the results of the stress analysis and the corresponding strength provisions, on the geometry and dimensions provided photogrammetrically, as well as on inputs provided by the various other studies involved in this project, as indicated in the Introduction. It is expected that a usable valve will be ready for testing in primates early in 1975.

Further series of molds need to be measured to determine the geometry of a variety of human valves such that the biologic spectrum is sufficiently bracketed. Also, when the prototype of the prosthetic valve becomes available, its geometry needs to be evaluated to compare design and performance data and to aid in further refinement of the prosthetic valve.

Acknowledgments

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(Abbreviations used: SPIE — Society of Photo-Optical Instrumentation Engineers, ASP — American Society of Photogrammetry, and UI — University of Illinois at Urbana-Champaign)

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1. Manuscripts should be typed, double-spaced on $8\frac{1}{2} \times 11$ or $8 \times 10\frac{1}{2}$ white bond, on *one* side only. References, footnotes, captions—everything should be double-spaced. Margins should be $1\frac{1}{2}$ inches.
2. Ordinarily *two* copies of the manuscript and two sets of illustrations should be submitted where the second set of illustrations need not be prime quality; EXCEPT that *five* copies of papers on Remote Sensing and Photointerpretation are needed, all with prime quality illustrations to facilitate the review process.
3. Each article should include an abstract, which is a *digest* of the article. An abstract should be 100 to 150 words in length.
4. Tables should be designed to fit into a width no more than five inches.
5. Illustrations should not be more than twice the final print size: *glossy* prints of photos should be submitted. Lettering should be neat, and designed for the reduction anticipated. Please include a separate list of captions.
6. Formulas should be expressed as simply as possible, keeping in mind the difficulties and limitations encountered in setting type.