DEVELOPMENTS IN SCIENTIFIC APPLICATION OF PHOTOGRAMMETRY TO STUDY OF ARCHITECTURE AND BUILDING SCIENCE

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Abstract

Recent applications of photogrammetry in this country and abroad include the rebuilding of demolished structure on the basis of photogrammetric drawings, the drawing of whole street facades in historic areas to judge the effect of proposed architectural additions, the study of structural deformations, and the recording of such elusive forms as soap film membranes as models in the structural design process.

Background

Photogrammetry is a highly developed science of measurement by means of photography providing geometrical data for basic research. The history of photogrammetry goes back more than 100 years to the pioneer work of Laussedat in France and of Meydenbauer in Germany.

The geometries of photogrammetry and of architecture coincide at several levels: the geometry

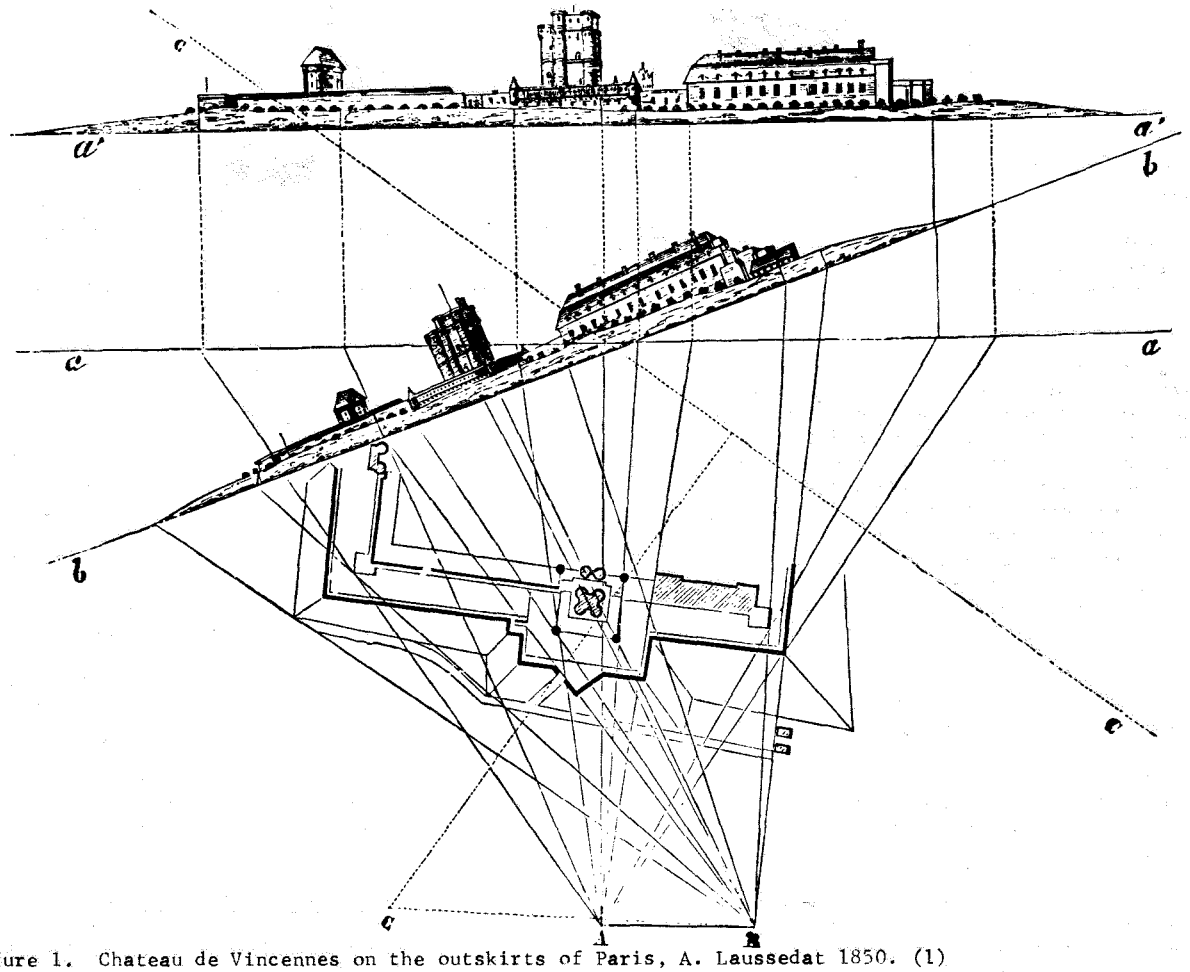

Figure 1. Chateau de Vincennes on the outskirts of Paris, A. Laussedat 1850. (1) Survey made by graphic system of intersecting lines of sight, using perspective views obtained with a sketchmaster.

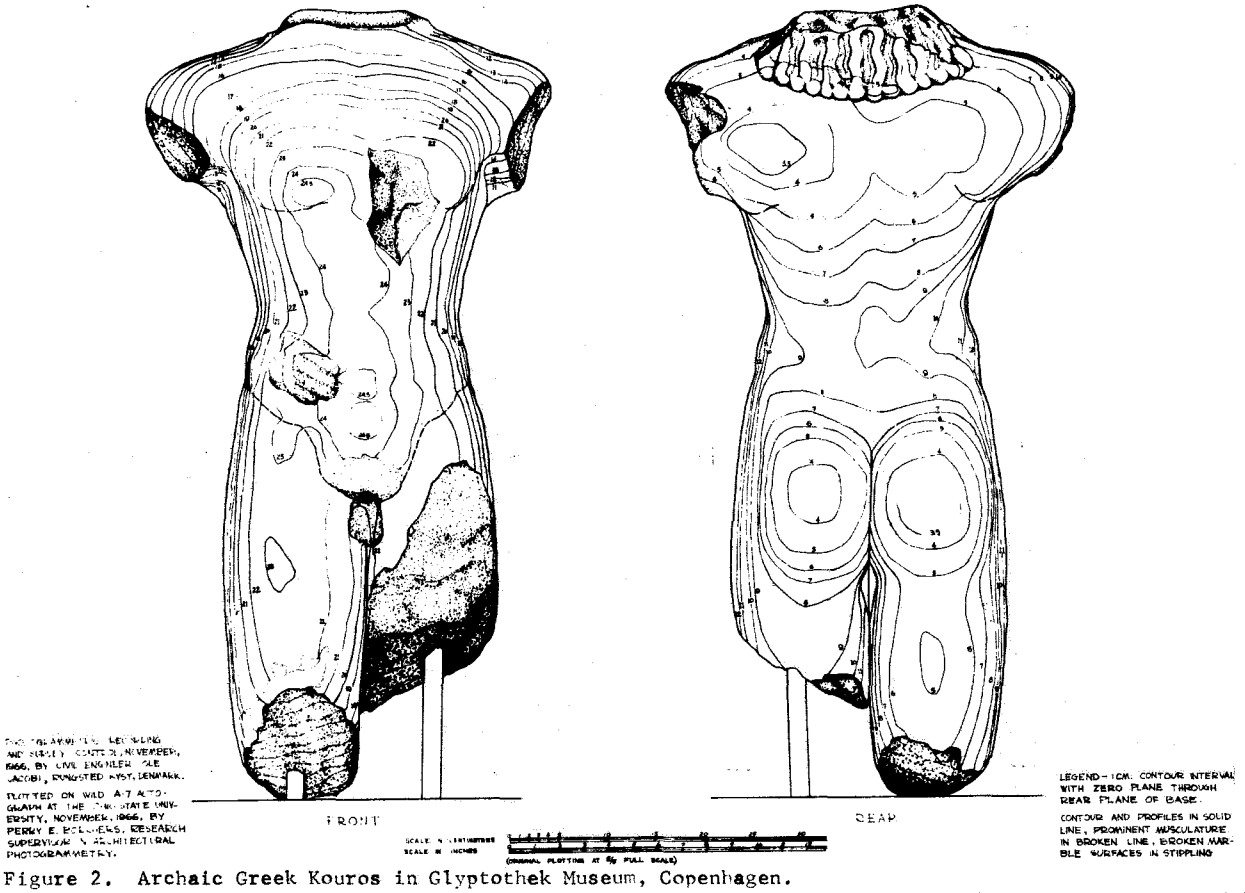

Figure 2. Archaic Greek Kouros in Glyptothek Museum, Copenhagen.
Plotted and drawn at The Ohio State University from photogrammetric plates sent from Denmark, 1966. (2)

of central projection in photography and in architectural perspective; the geometry of stereophotogrammetry and of binocular visual perception of architecture and space; the geometry of orthographic architectural drawing and of rectangular coordinate systems in space, photogrammetric plotting and orthoprinting. Analytical photogrammetry and architectural computer graphics are based on similar formulas, except that photogrammetry, dealing with accuracy limitations of the eye, lenses, plates, emulsions and instruments, has a developed theory of error and adjustment computations.

Depth dimensions and the contours expressing depth in drawing are readily accessible data in photogrammetric plotting; and photogrammetric drawings which contain both planimetric detail and contours are more complete in the expression of geometric data than orthographic architectural drawings, even with their conventions as to weight of line and outline. Architectural forms which were freed from rectangularity to become sculptural and innovative in structure have required photogrammetric means to record and photogrammetric contour drawing to express their geometry. Construction drawings of complex architectural models recorded photogrammetrically have appeared like topographic maps.

The photographic plates which - with survey control - constitute the initial photogrammetric record carry a degree of detail, particularly of surface texture, which exceeds that which can be drawn. Limitations on the reproduction of photographs in this paper prevent a properly-balanced illustration of photogrammetric methods and resources - of photogrammetric plates with fiducial marks to determine the principal point in the image, of stereopairs as three dimensional illustration in technical publications, of rectification and orthoprinting. These last are means of converting the geometry of central projection in the photograph to the geometry of orthographic projection with the least loss of photographic detail and the least intervention (and cost) of plotting machine operators and draftsmen.

Photogrammetric Plates and Survey Control

The photogrammetric plate - with its survey control of camera positions, camera orientation and selected elements within object space in the photographic image - contains all the information which can later be abstracted in draw-

ing or as coordinate data. It is the first record, limiting all future records according to the extent of photographic coverage, accuracy and geometric distribution of survey control in the photographic image, accuracy of calibration of camera body and lens, and flatness and quality of resolution of the photographic emulsion. All of these matters are subjects of continuing research and improvement in the profession of photogrammetry.

The typical photogrammetric cameras for architectural surveys are phototheodolities - mounting a precise camera upon a surveying instrument - or stereocameras with fixed bases between two cameras for simultaneous photographic exposures. The cameras have rigid bodies to maintain the geometry of interior orientation and fiducial marks recorded on the photogrammetric plate to establish the principal point of the image, i.e., the intersection with the image plane of a perpendicular line through the center of the lens, ideally the camera axis. Recently, less expensive cameras than those especially built for photogrammetric use by major instrument manufacturers within Europe such as Wild, Zeiss, Officine Galileo, Poivilliers and others, have been adapted for close range and terrestrial photogrammetry - among which architectural surveys are included - by calibration in photogrammetric institutes, by addition to the camera body of fiducial marks to establish the principal point in the image, by the addition of glass plates against which to flatten the photographic film - sometimes with reseau markings to determine film warping at the time of exposure and later, and by determination of distortion in the lens as a means of knowing the error in subsequent analogue plotting or of compensating for error in the image coordinates in computer programs of analytical photogrammetry. Rollei and Hasselblad cameras are among those adapted in this manner to fix the interior orientation. The elements of exterior orientation, i.e., the space coordinates of the camera position, the orientation angle and tilt of the camera axis and the rotation of the image plane around the camera axis, must then be determined by separate surveying instruments or by computation of lines of sight from elements of survey control targeted in object space and recorded in the photographic image.

When photogrammetric plates and films are taken as stereopairs, i.e., along generally parallel camera axes with the camera stations displaced on a line generally perpendicular to the camera axes, there is the advantage of stereoscopic viewing of an optical model. This reproduces binocular vision in object space with increased acuity of depth perception because of a greater base in photography than that which separates the human eyes. For architects and craftsmen associated with architectural restorations the stereopairs directly viewed can be the most impressive element in the photogrammetric process.

Photogrammetric stereopairs with their survey control can be transmitted in space - Figure 2, or consulted after the lapse of time - Figure 3, drawn in 1970 from plates taken in 1963. The proposed rebuilding of the great entrance arch of the Old Chicago Stock Exchange by the city of Chicago means that these plates will be plotted and drawn again in 1972.

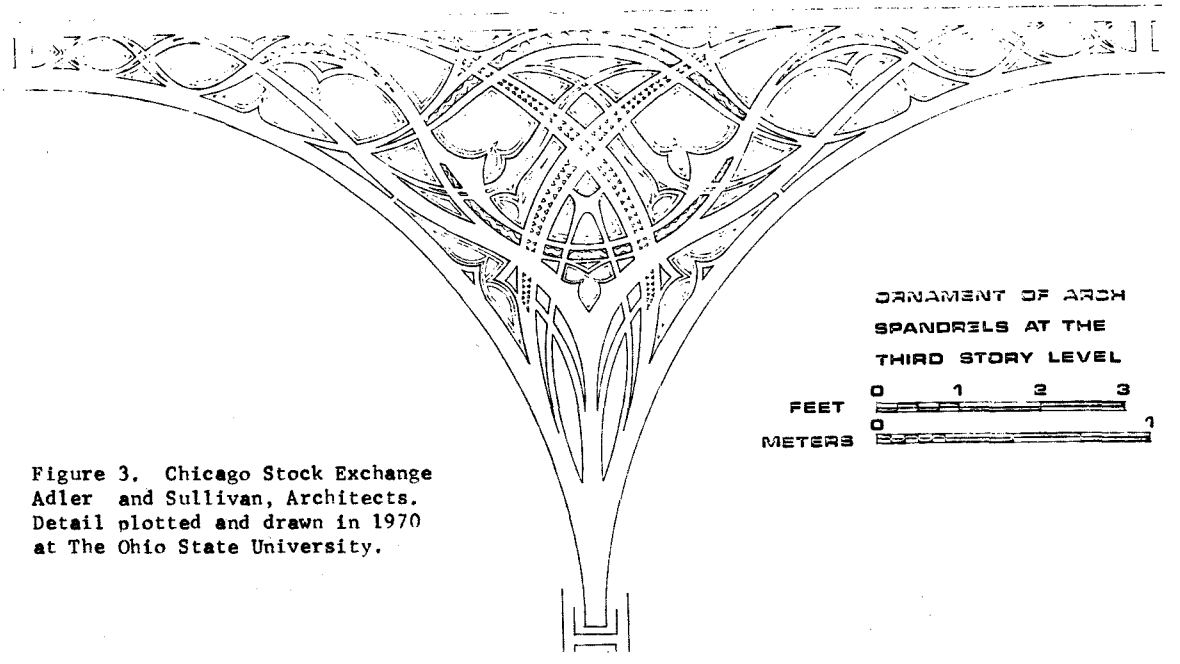

Figure 3. Chicago Stock Exchange
Adler and Sullivan, Architects.
Detail plotted and drawn in 1970
at The Ohio State University.

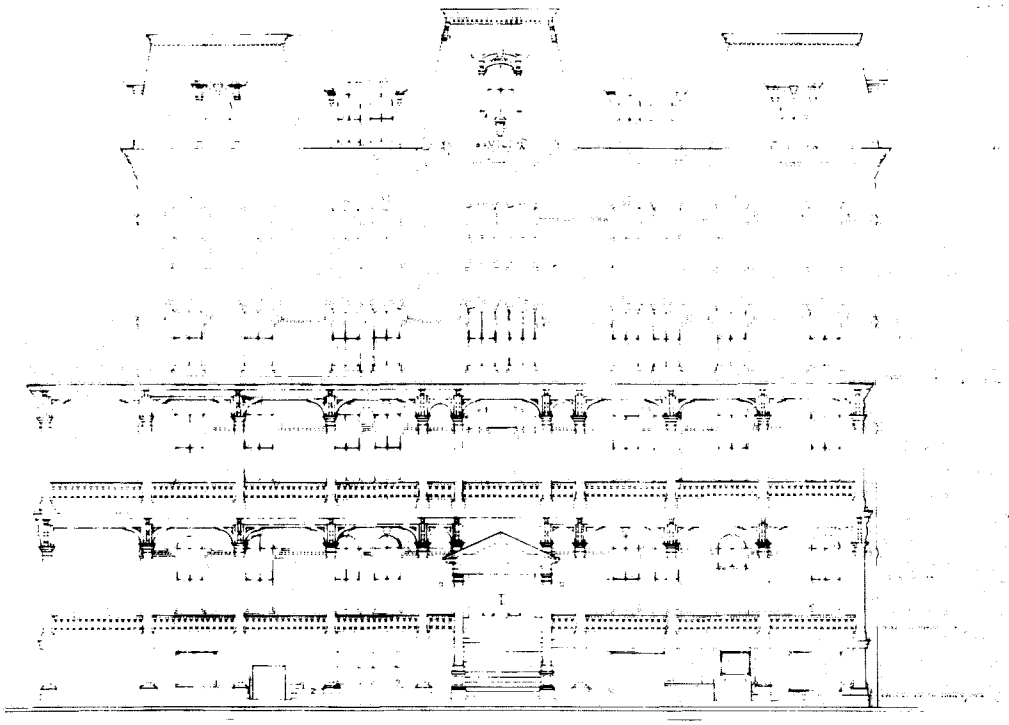

Figure 4. South Elevation of the Pavilion Hotel, Montpelier, Vermont.
Part of the State of Vermont Capital Complex, Robert Burley and Associates, Architect
Recorded photogrammetrically 1969 and drawn at The Ohio State University 1970.

Photogrammetry in the Rebuilding of Demolished Structure 1969-1971

Historic architecture has been the chief subject of architectural photogrammetry, and imminent demolition has been the chief spur to photogrammetric recording of US architecture. Since 1956, more than 30 contract projects in architectural photogrammetry have been carried out at The Ohio State University, recording some 70 historic buildings and engineering structures, chiefly for the Historic American Buildings Survey and the Historic American Engineering Record of the National Park Service, U.S. Department of the Interior, and preparing more than 150 sheets of drawings. Complementing the National Park Service summer program of hand measurement by teams of student architects, photogrammetry has been the most efficient system for recording structures which are complex, sculptural or deformed, tall, difficult or dangerous of access, or which have little time before demolition. Several historic buildings exist now only in the photogrammetric record of the HABS.

In the fall of 1969, a historic building was recorded for the new purpose of rebuilding after demolition. The Pavilion Hotel in Montpelier, Vermont, was part of the State Capital Complex planned by Robert Burley and Associates; and it was scheduled for gutting and rebuilding of new state offices within its outer walls, when the contractor, the Pizzigalli Construction Company, bid half a million dollars less to demolish the building entirely and rebuild the outer walls as well as the inner core. On short notice, an OSU photogrammetric team recorded the outer walls before demolition in October 1969; the stereopairs were plotted and drafted at OSU during the winter in time to help guide rebuilding in the spring of 1970. A print of the drawing in Figure 4 was prominently displayed at the front of the construction site during the work, which is now complete.

The general accuracy of photogrammetric plotting in projects of this kinds, based on residual discrepancies at survey control points chiefly located in the plane of the camera horizon, is to within about 1/1000th of major dimensions. The vertical dimensions of the Pavilion Hotel were evened off to eliminate sags and broken masonry, easily measurable in the stereopairs and evidence of uneven foundation settlement. (The rebuilding was moved ten feet on the site.)

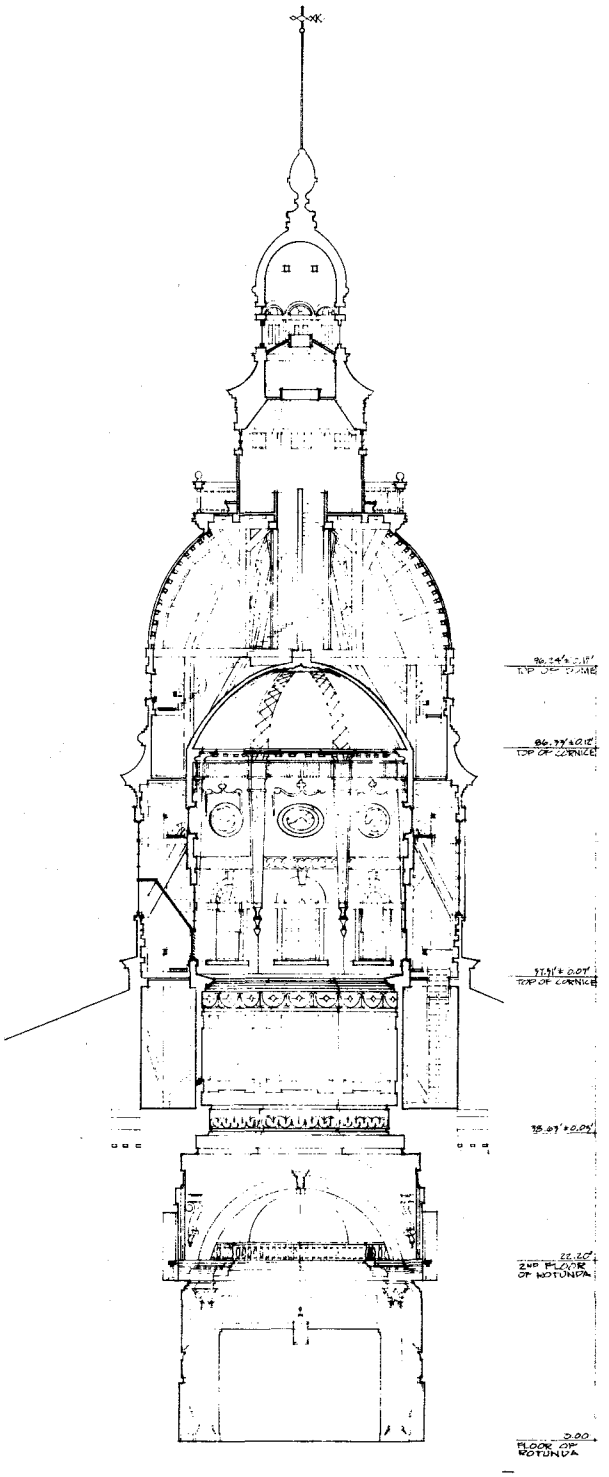

Figure 5. Old Statehouse, Annapolis, Maryland. Section through the rotunda and cupola recorded photogrammetrically 1970 and plotted and drawn at The Ohio State University 1970 71.

Again, in November 1971, a photogrammetric recording was made in haste of the Exchange Room of the Old Chicago Stock Exchange by Adler and Sullivan, 1893, when demolition revealed a false ceiling and uncovered original Sullivan plaster, stained glass and stenciled ornament which the Art Institute of Chicago is determined to restore in a museum room of the original dimensions as measured by photogrammetry.

Photogrammetry in Historic Preservation

Among photogrammetric projects concerned with the preservation of historic architecture the most recent at The Ohio State University has been the recording of the rotunda and cupola of the Old Statehouse in Annapolis, Maryland, in which George Washington resigned his commission as general of the Continental Army in 1784. Government buildings in Maryland had been the targets of bombing; and this historic building was well-guarded at the time of photogrammetric recording of its heavy timber structure.

Figure 5 is a section through the rotunda and cupola of the Old Statehouse. This drawing was assembled from plottings and measurement of the following stereopairs:

From camera stations upon a rooftop at close quarters to the octagonal cupola, stereopairs of the exterior side facade with horizontal camera axes and then with camera axes inclined upwards 24°, with manual measurements upon the building serving as survey control.

From camera stations in the interior - tripods at ground floor level of the rotunda - stereopairs of the interior walls with horizontal camera axes and then with camera axes inclined upwards 18°, with camera horizon markings upon the walls and columns serving as survey control.

Finally, with the photogrammetric camera removed from its theodolite base and laid with plateholder back upon the floor and lens pointed upwards, a stereopair up the tall and narrow interior of the cupola, with nearly vertical camera axes, and survey control consisting of two measuring tapes stretched at right angles to each other horizontally across the cupola between windows at its mid-height and - establishing a positive vertical coordinate axis in object space - a weighted measuring tape hanging from mid-height in the cupola to the floor upon which the camera was resting.

Spaces and structural elements between interior and exterior domes were recorded in film stereopairs with the Hasselblad Supreme Wide Angle camera. The control provided by major dimensions from the plotting of phototheodolite stereopairs together with a few additional dimensions for scale sufficed for completing the drawing.

Photogrammetric Instrumentation

Besides phototheodolites and stereocameras another group of photogrammetric instruments are those used to abstract the data recorded on the photogrammetric plates. The simplest are stereoscopes with parallax bars for direct measurement and rectifiers for projection. Then there are mono- and stereocomparators of varying degrees of electronic coordinate readout, analogue plotting instruments of special or universal application, orthoprinters, and automatic and analytical plotters programmed with computers. Each of these instruments has an appropriate and efficient application in architectural photogrammetry according to varying requirements of accuracy, speed of data production, adaptability to routine or to diversity of use, and skill demanded of the operator.

Pocket and mirror stereoscopes with parallax bars are easily portable instruments for viewing stereopairs as optical models and for taking off measurements of horizontal parallaxes from which depth in space and scale of dimensions can be calculated with rough accuracy.

Rectifiers are precision enlargers with rotating and tilting projection tables on which the true orthographic proportions of an architectural plane can be reestablished and printed when the inclination and angles of the camera axis in relation to the architectural plane during the photography are reproduced in the rectifier. "Single-picture photogrammetry" was the early name for this process, providing satisfactory accuracy and exceptional detail of surface texture, masonry joints, stained glass, mosaic and fresco on essentially plane surfaces. Distortion appears in the projected image for all elements before or behind the rectified plane, requiring another method of correction.

Mono- and stereocomparators are instruments - sometimes of the highest order of accuracy with electronic and tape readout - for the measurement of image coordinates as data for calculation of object-space coordinates. Stereocomparators allow the simultaneous measurement of image coordinates in one photogrammetric plate and x and y parallax in a second plate, and are the most effective instruments for the measurement of structural deformations and small building movements. Both mono- and stereocomparators can be used in the process known as analytical (or computational) photogrammetry.

Analogue plotting instruments use stereopairs to recreate optical models - by projection or by mechanical means - through which an operator can move a measuring mark, touching elements and simultaneously drawing them in orthographic projection. This is stereophotogrammetry. The Ohio State University has a Wild A7 Autograph analogue universal plotting instrument of first order accuracy. It can accept plates from photogrammetric cameras of varying focal lengths. All the elements of exterior orientation can be adjusted with a greater accuracy than that recorded by the phototheodolite. It can be used to plot both aerial and terrestrial stereopairs, which means, in architectural photogrammetry, both elevations and horizontal sections and plans can be plotted, or, in the case of the vertical stereopairs upwards under the cupola of the Old Statehouse in Annapolis, both horizontal sections with ceiling plan and vertical sections with interior elevations could be plotted. Gears allow a change of scale of 24 times in the plotting. These are characteristics of a universal plotting instrument, having yet one disadvantage in the skill, particularly in orientation, required of the operator of it.

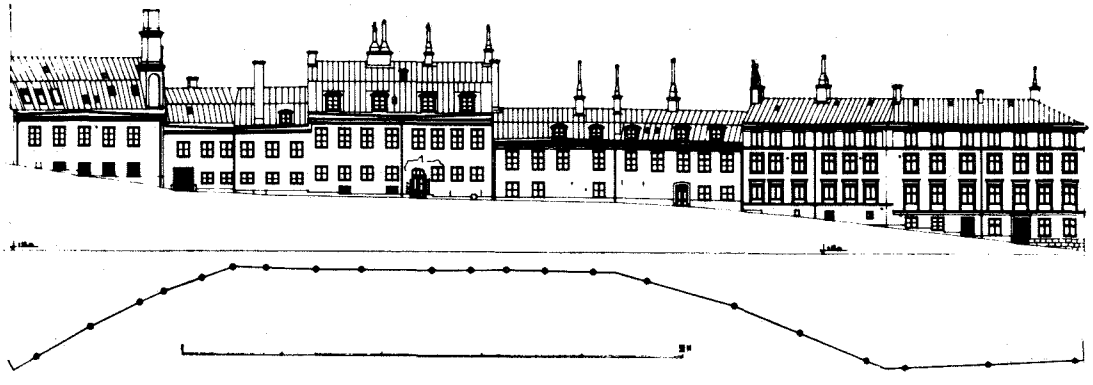

Figure 6. Ten building fronts on a narrow curving street, drawn from analytical photogrammetry at the Royal Institute of Technology, Stockholm Sweden. The lower line shows a traverse of control points in plan. (3)

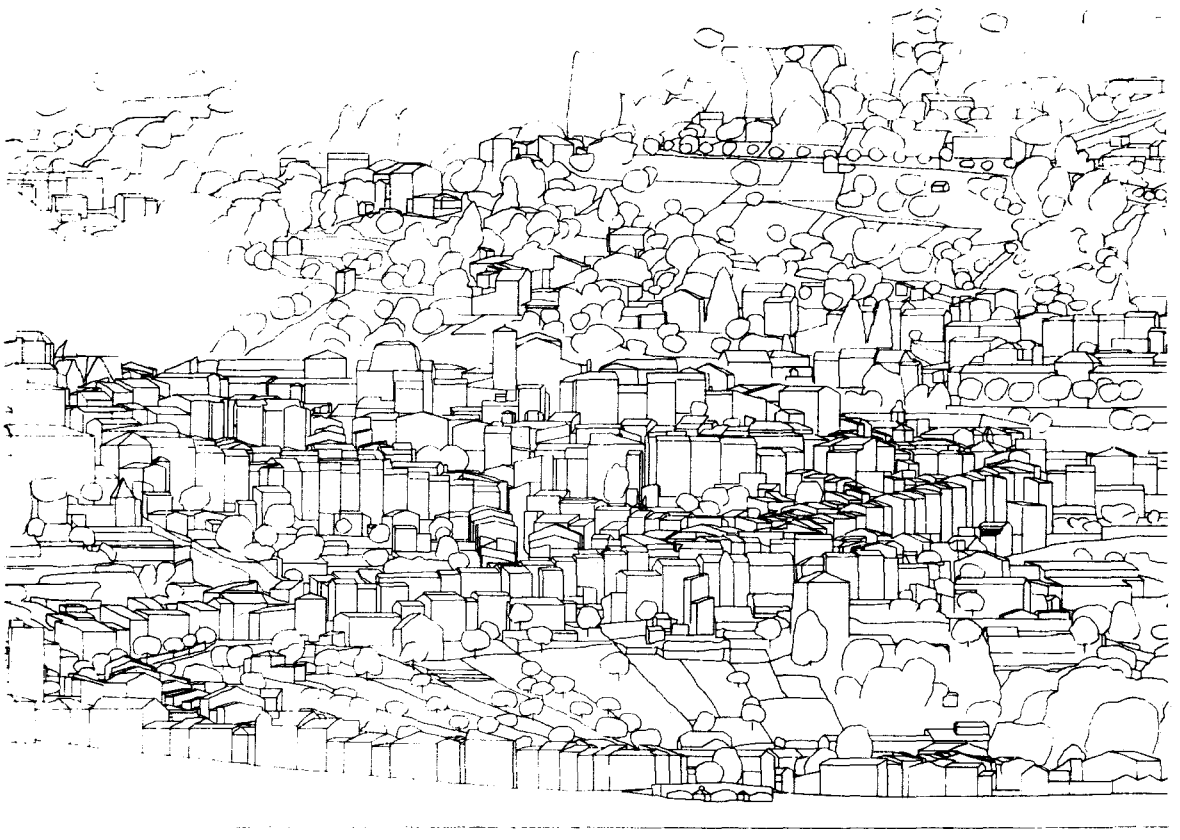

Figure 7. Portion of an elevation of the city of Thiers obtained from stereophotogrammetry. Document of the Institut Géographique National, France. (4)

Orthoprinters and automatic and analytical plotters have been developed to reduce time and reliance on the operator. Orthoprinting produces data from stereophotogrammetry similar to that produced by rectification in single picture photogrammetry. The process requires operator or automatic control of depth in the optical model while the orthoprinter scans and prints photographic data. As yet, no automatic control has been able to compensate for the sudden changes in depth of the architectural optical model and for those planes seen - often in only one image of a stereopair - which should be projected as a line edge in the orthoprint. Automatic and analytical plotters are variously adapted with computers automatically processing image and optical model coordinate data to calculate relative and absolute orientation of the photographic plates, to calculate coordinate data in object space with digital or analogue printout, and to recognize and print contours of depth. The automatic systems still require the discrimination of an operator - perhaps in the future a programmer - to distinguish those features worth recording, i.e., in architecture the wall instead of the ivy.

Architectural Photogrammetry in Europe

There is a much greater use of photogrammetry in Europe than in this country for recording and measuring architectural subjects; and this is particularly evident in the field of preservation of monuments and historic areas. These last - as they have almost ceased to exist in the United States - should be defined as those exterior spaces whose special and pleasing character is established by the coherent but otherwise unexceptional facades of whole blocks and streets and neighborhoods of buildings. Under the pressures of the automobile, tourism and economic growth many of these historic areas are being penetrated by new building with an impact on the area which cannot be anticipated without adequate drawings of the present facades in relation to proposed new structures.

Photogrammetric sections have been established in many ministries concerned with the cultural and architectural heritage; and new instruments and techniques are being specially developed for the recording of long facades upon narrow streets. Figure 6 shows a Swedish solution to the problem employing analytical photogrammetry

in the measurement of image coordinates in convergent photographs - not stereopairs - angled up and down the street, with computer calculation of coordinates in object space for all major lines of the buildings. (3) In similar street situations throughout Austria another solution was adopted by their Federal Service of Historic Monuments - making stereophotogrammetry routine for relatively unskilled technicians (architects) with standard stereocameras of fixed base and a limited number of inclinations matched with an analogue plotting instrument of similar limitations, allowing productionline drawings from saturation stereophotography at short distances. Among the solutions proposed in France within the National Geographic Institute to the need for extensive street facade drawings has been a class of "expressive" drawings, with allowable errors of as much as 5%, which can be rapidly assembled from the rectification of multiple single photographs.

Photogrammetric Measurement of Building Movement

The application of architectural photogrammetry with the most rigorous requirements of accuracy and greatest diversity in conditions of photography is the recording and measurement of three-dimensional movement in architecture and engineering structure.

The main characteristic of photogrammetric measurement of such movement is the abstraction as basic data of relative measurements between pairs of plates photographed at different times with the same camera at the same camera station along the same camera axis. The most efficient instrument of measurement is the stereocomparator. The correspondence between successive pairs of plates, measured together, effectively eliminates systematic error caused by lens defects and makes possible the measurement of movements of structure with greater accuracy than measurement of the structure itself.

Radial error caused by the lack of flatness of photogrammetric plates and emulsions has been the most substantial error in the process, but even this can be corrected by relative measurements, by a system described elsewhere. (5)

With the correction of relative radial error, the standard error of measurement in the photographic image has varied from 1/9000 to 1/50,000 of the width of the image with various photogrammetric cameras used at The Ohio State University and the Royal Institute of Technology in Stockholm. The propagation of this error by projection into object space must be computed to determine the significance of measured data. (see Figure 8) Even thermal sources of struc-

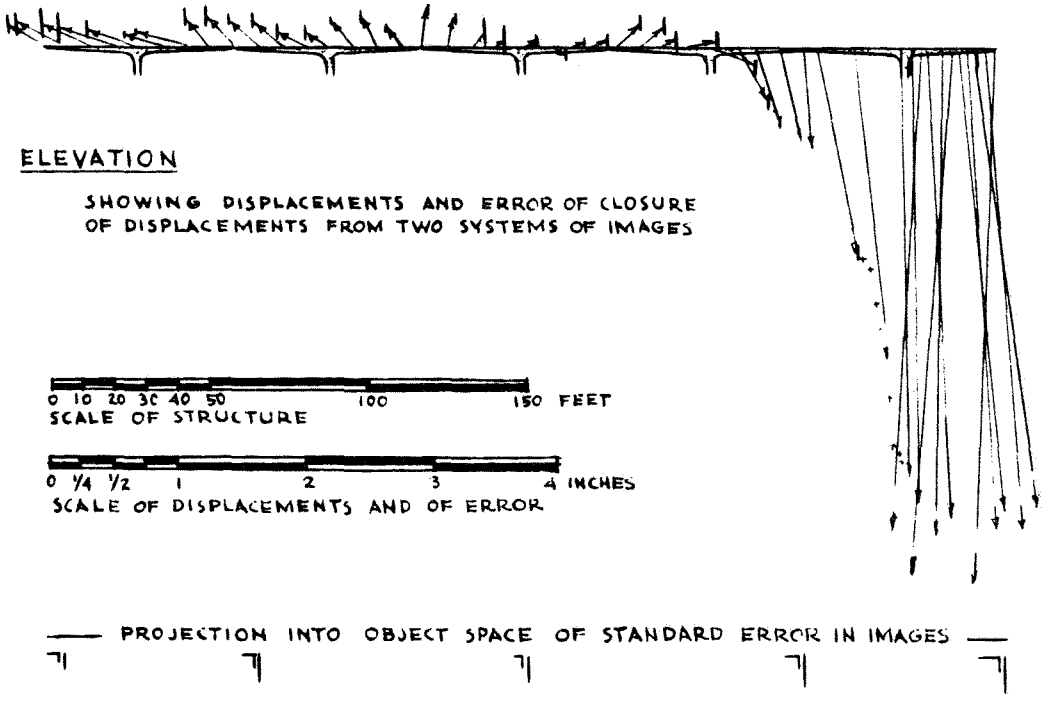

Figure 8. Displacement measurements of five hyperbolic paraboloids at Scioto Downs racetrack (5) during curing of concrete of final paraboloid and with change of temperature. Photogrammetric recording and measurement at The Ohio State University and the Royal Institute of Technology, Stockholm, Sweden.

tural movement can be sought photogrammetrically over an entire structure. One of the advantages of photogrammetry in this search is that, recording hundreds of potential measurements in a moment of time, structural movement may be discovered where it was never anticipated.

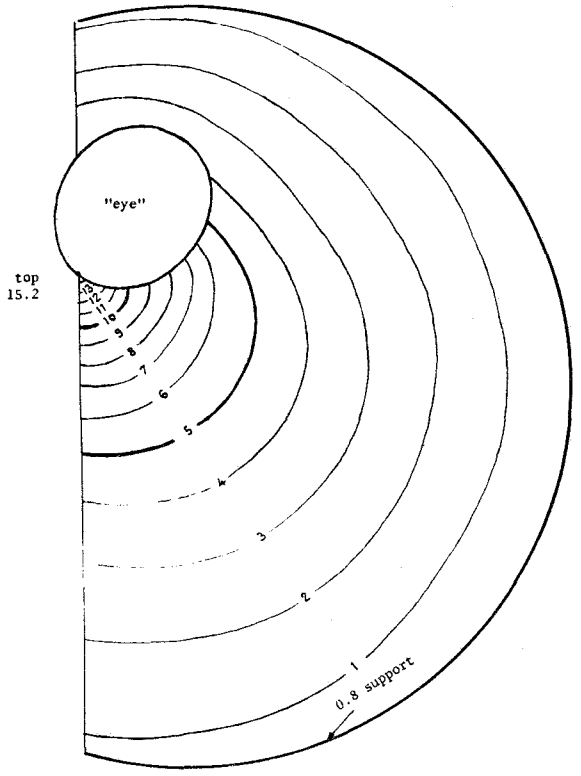

Figure 9. Photogrammetric contour map of the front surface of a soap film membrane with an eccentric "eye" based on a circular support.

Photogrammetry in the Design Process

There has been an earlier account of architects who designed in sculptural model and were unable to dimension their conception for construction drawings until the model had been photographed and plotted in contours by stereophotogrammetry to establish some 1700 locations of reinforcing steel in a concrete shell. ( )

The west German engineer and architect Frei Otto has designed unusual tension structures such as the roof of the German Pavilion at Expo 67 in Montreal from observation of thin soap membranes which he transformed into wire models. At the University of Stuttgart photogrammetric research has now established a method of direct measurement of the unstable soap membrane - which had earlier eluded effective photographic recording because of transparency and near-invisibility and reflections which are never seen stereoscopically in the plane of the reflecting surface. The method, which has been published (6) with results illustrated in Figure 9, was to mix a fluorescent chemical of otherwise neutral characteristics into the soap solution, expose the soap membrane to ultra violet radiation through a screen casting a texture of shadow upon the surface (which elsewhere emitted low energy fluorescent radiation), photograph with stereocameras, measure with a comparator, and evaluate analytically to produce contour maps. This method can now be a part of the design process, as soap films have been studied for over 50 years to solve torsion problems as well as the problems of tension structures.

Summary

Photogrammetry is a science of measurement providing geometric data for basic research in many fields. According to Lord Kelvin -

> When you can measure what you are talking about and express it in numbers you know something about it. When you cannot measure it or express it in numbers your knowledge is of a meager and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely attained to the stage of science, whatever the matter may be.

The natural forms of photogrammetric data are particularly appropriate to architectural use. The single photograph can accept the architect's perspective drawing upon it; and the rectified photograph can accept his orthographic elevation. Stereopairs reproduce binocular vision in space, and in combination with orthographic drawings prepared photogrammetrically, allow the most direct comparison of actual dimensions seen in drawings and apparent dimensions seen in space. A theory of error of binocular vision, i.e., of uncertainty of depth perception, can be taken from photogrammetry into architectural space to explain or anticipate the optical illusions which can be exploited or corrected by the architect. (7) Architectural literature could, with great advantage, be illustrated with stereopairs in the manner they appear in the technical literature of photogrammetry.

Photogrammetry and architecture are related as a geometrical science to a geometrical art. The useful applications to architecture of the science of photogrammetry have barely begun to be exploited.

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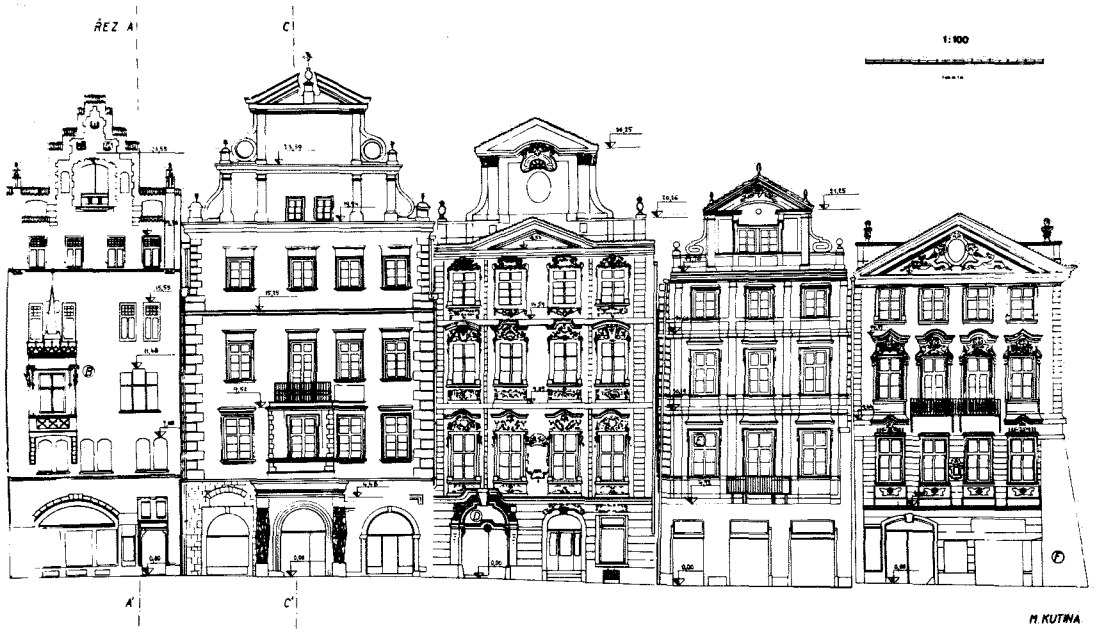

Figure 10. Facades of houses on the main square, Prague, Czechoslovakia, courtesy of the Czechoslovak State Institute for the Protection of Monuments.