Dimensional Characterization of a Large Aircraft Structure by Photogrammetry

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ABSTRACT: An application of industrial photogrammetry to the dimensional characterization of a large aircraft structure is described. The aim of the project was to establish the degree of structural correspondence between the as-built development fixture for a large transport aircraft and its design which was embodied in a computer-aided design (CAD) database. The measurement task involved the photogrammetric positioning to 0.2-mm accuracy of more than 1400 points on interior loft surfaces. Aspects of the photogrammetric survey – specifically, network design considerations, photography, and data processing – are discussed, and an analysis of the results is presented.

INTRODUCTION

ONE OF THE PRINCIPAL STEPS involved in designing and building a new aircraft is the fabrication of a development fixture (DF), which is essentially a mock-up of the aircraft. The structure of the DF should naturally conform to its CAD model, and the degree of dimensional conformance needs to be sufficiently precise to allow the transfer of further design details (e.g., for wire-harnessing, hydraulic lines, etc.) between the CAD and as-built models.

The DF is built with the aid of a large tooling jig which is a structural steel framework. Within and around this framework is built an aluminum, wood, and steel full size replica of the aircraft. This model is utilized to locate or assist in the fabrication of many of the air-frame assemblies and sub-assemblies. The spatial positioning of assembly components is carried out within the XYZ cartesian coordinate system of the tooling jig, which also corresponds to the aircraft coordinate system to which the CAD model is referenced.

Figure 1 shows the DF for the new C-17 military transport aircraft which is being built by the Douglas Aircraft Company. The fixture is rather large and complex in construction, being some 43 m in length and 6 m in diameter at the mid section. Under the aluminum skin there lie upwards of 70 ribs and 80 longitudinal stringers (longerons). Although careful attention is paid to dimensional integrity in the fitting together of sub-assemblies of the DF, there is no straightforward means for immediately verifying the positional accuracy of the final assembly. To ascertain this, an independent method of measurement is required.

In the case of the C-17 DF, a dimensional characterization of the interior loft surface framework was sought. In coordinate measurement terms, this translated to a need for the XYZ coordinates of some 1400 points (mostly positioned on ribs) to be measured in the reference coordinate system of the tool. What first appeared as a straightforward requirement revealed itself to be somewhat more complicated on closer inspection. For example, all measurement points of interest were inside the DF, whereas all XYZ reference points were positioned external to the structure on the framework of the tool. Intervisibility between the tool and the measurement points was very restricted, being limited to the main cargo door, cockpit windows, and four side doors. Moreover, points were distributed over the length of the DF from the front of the cockpit to the rear fuselage bulkhead where tool framing severely limited visual access to target areas, as shown in Figure 2. Basically, the object point configuration called for targets at 60-cm intervals around each of the ribs, but only above the cargo floor level (floor reference plane).

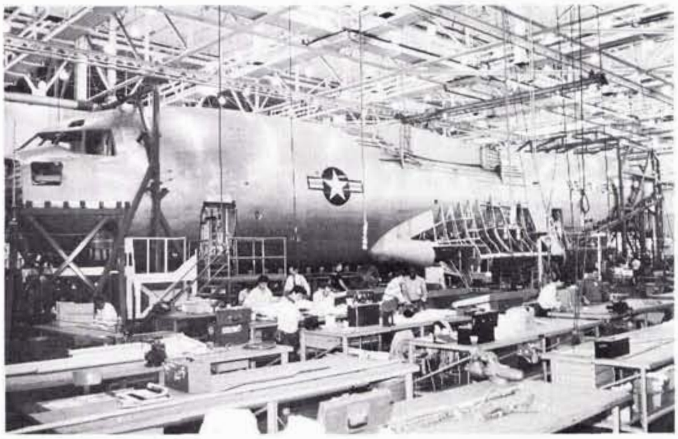
FIG. 1. The C-17 development fixture.

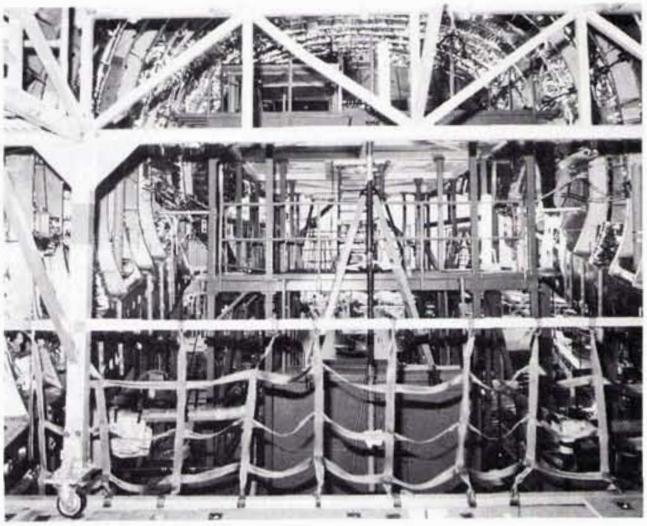
FIG. 2. Tail section interior showing tooling structure, as viewed from the rear of the main cargo section.

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Of the three-dimensional measurement techniques available for industrial applications (including optics, lasers, and theodolites), photogrammetry is without doubt the most practical approach for a measurement task such as the DF. Indeed, it is arguable that it is the only feasible approach, because alternative techniques such as digital theodolites and laser trilateration are not readily suited to this endeavor. In the case of theodolites, the number of instrument setups would be excessive, the accessibility and stability of set up locations is questionable, and, perhaps most importantly, an extended observation period would be involved. Moreover, during the observing period other work on the DF would have to be severely curtailed or stopped while people and workstands were removed to eliminate obstructions and sources of extraneous vibration and movement. The major problems with laser trilateration in this case would be the establishment of an effective targeting strategy, instrument stability concerns, the number of instrument setups required, and maintenance of a uniform coordinate system throughout the 43-m length of the DF.

Accordingly, photogrammetry was chosen as the method of dimensional measurement for the DF. While this technique was judged the most suitable, it was not envisioned that the project would be a straightforward one. The purpose of this paper is to describe the photogrammetric measurement process as applied to the DF and to detail some of the specific problems which had to be overcome in establishing a photogrammetric network capable of measuring all points to an accuracy level (RMS 1-sigma) of 0.2 mm.

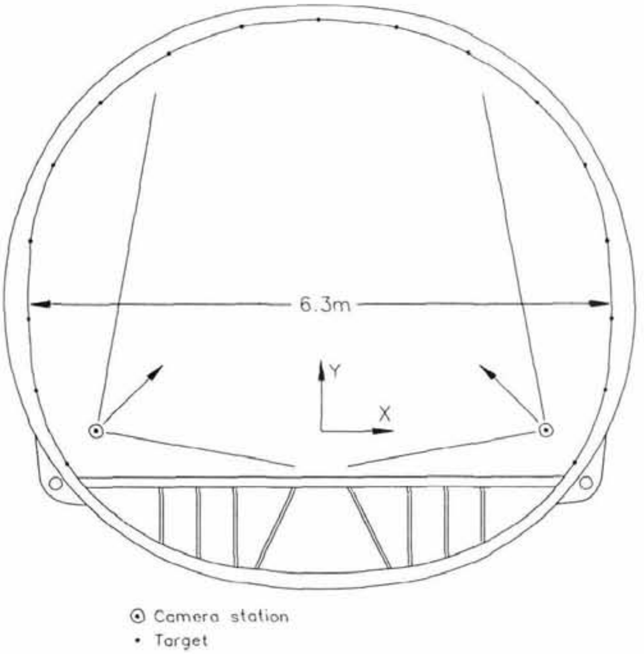

FIG. 3. Coverage provided by camera stations in the mid section.

NETWORK DESIGN

From a structural measurement point of view, the interior loft surface area of the DF could be considered as comprising three distinct parts: the cockpit, the main cargo bay, and a tail section. The boundary between the main cargo bay and tail section was established by the tooling jig structure rather than by any abrupt change in structural characteristics between the two sections. In length, the cockpit framework covered close to 3 m, the mid section 29 m, and the tail section 11 m. In carrying out preliminary planning for the photogrammetry, it was deemed both logical and most practical to consider each of the three sections as a single measurement task. Following the dimensional characterization of each separate section, all object target point coordinates would then be mathematically transformed into the common reference coordinate system of the tool. In the following discussion, therefore, we deal with a different photogrammetric network design for each section.

MID SECTION

The main cargo bay section can be thought of as an open cylinder with transverse ribs. Target points covered an arc of approximately 250° from floor level to floor level as shown in Figure 3. Coverage of such a large angular field within the "cylinder" necessitated a wide-angle camera, and the camera chosen was the GSI CRC-1 (Fraser & Brown, 1986) fitted with a 120-mm lens. This camera/lens combination yields a working view angle (along the image coordinate axes) of approximately 85°.

As can be seen from Figure 3, the positioning of camera stations some 40 cm in from the side walls and 40 cm off the floor afforded full coverage of all points on a rib. Overlapping coverage was also provided at the upper centerline area where the overlap spanned about 2.5 m. The average camera-to-object distance for the camera stations shown in Figure 3 was around 6m, which implied a photographic image scale of about 1:50. With this strong multi-ray imaging geometry and film reading accuracy of one micrometre, a photogrammetric network with this imaging scale will yield object point coordinate accuracies better than the 0.25-mm upper bound that was set for the measurements. Through network design simulation, the precision of object point coordinates was to be quantified prior to the actual measurement taking place.

In selecting an imaging geometry for the longitudinal direction a mixed "normal" and convergent arrangement was adopted. Provision of "normal" geometry had two notable benefits. In the first instance this configuration provided good coverage of the "cylinder" walls and was least influenced by target foreshortening. Second, stereopairs were provided for possible later mapping in support of wire-harness and plumbing design. Camera station locations and viewing directions are indicated in Figure 4. The base length between adjacent "normal" camera stations gave rise to points in the near field (close to the roof centerline) being imaged in two or three photos, whereas points in the far field (mid-height areas of the wall) were seen in three or four.

The addition of the convergent stations was necessary for the following reasons. First and foremost, the convergent imaging arrangement improved intersection geometry and therefore enhanced triangulation accuracy. Except for a few three-ray points near floor level on some of the ribs, all targets were imaged in at least four photographs and most were covered by five to seven. Second, the greater longitudinal coverage of the convergent images coupled with the stronger geometry, suppressed the possibility of warping in the long narrow network. Last, the convergent images covered a greater angular field over the roof area, and this eliminated the possibility of any "hinging"' effect between the two sides of the network about the upper centerline area.

In building the network, the STARS interactive network design simulator (Fraser and Brown, 1986) was used to verify everything from point coverage, target foreshortening, and focus details, through to the generation of anticipated standard errors for the *XYZ* coordinates of triangulated points. Two fictitious photographs as generated by the simulator are shown in Figures 5 and 6, one for a "normal" and one for a convergent view. For the mid-section network, which comprised 38 camera stations and 990 points, accuracy estimates (RMS 1-sigma) for the

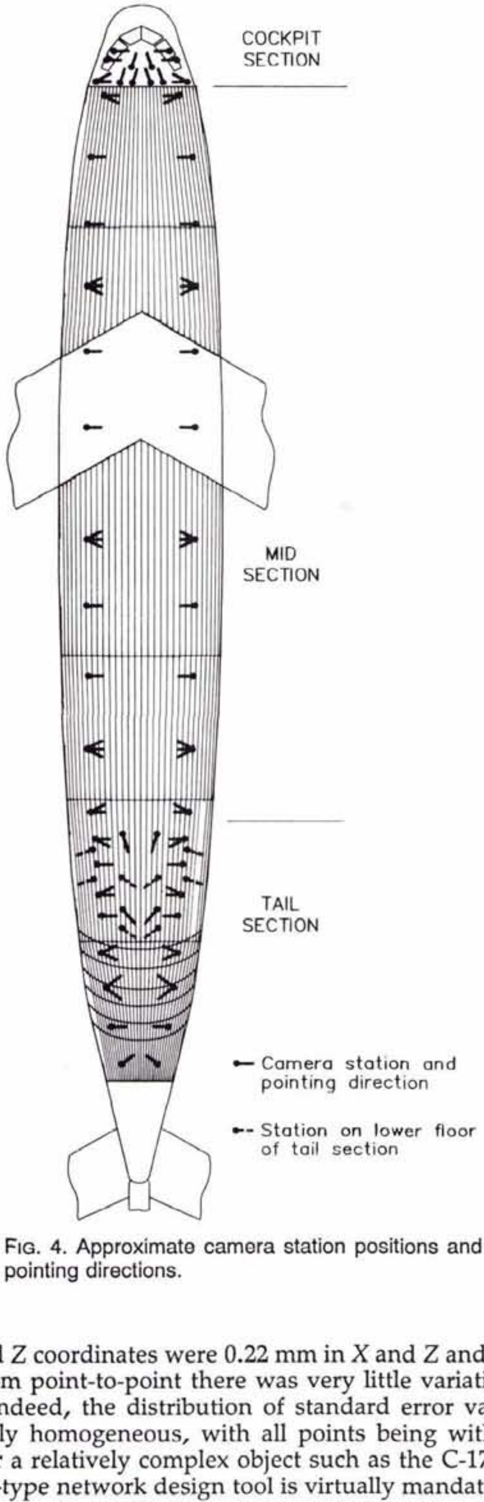

FIG. 4. Approximate camera station positions and pointing directions.

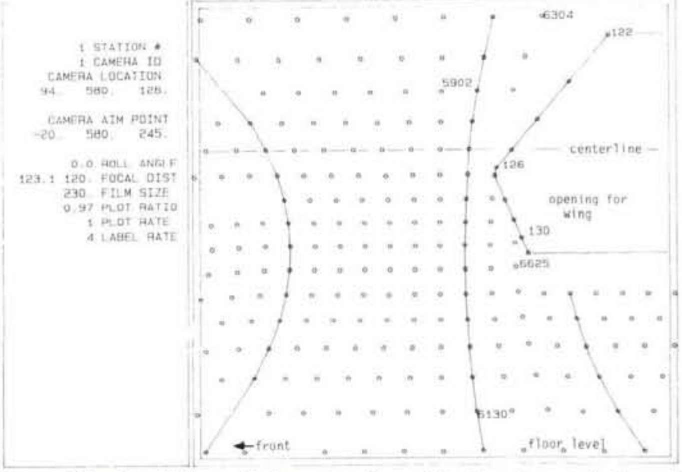

FIG. 5. Simulated "normal" view of portion of the target array in the mid section.

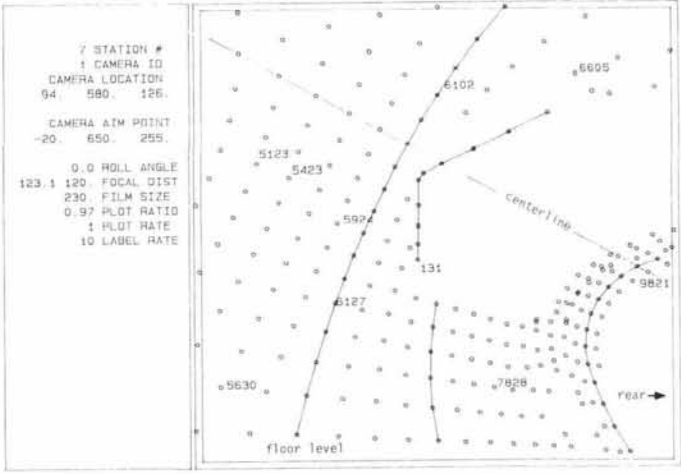

FIG. 6. Simulated convergent view of portion of the target array in the mid section.

X, *Y*, and *Z* coordinates were 0.22 mm in *X* and *Z* and 0.17 mm in *Y*. From point-to-point there was very little variation in accuracy; indeed, the distribution of standard error values was reasonably homogeneous, with all points being within tolerance. For a relatively complex object such as the C-17, the use of a CAD-type network design tool is virtually mandatory given the difficulties in establishing photographic coverage and target foreshortening information via simple graphical techniques.

COCKPIT SECTION

As opposed to the main cargo section network, that for the cockpit was a reasonably straightforward design task. Here there was no uniform transverse rib structure, and targets were placed at points of interest throughout the cockpit area, again only above the floor level. One factor which complicated the geometry somewhat, and necessitated extra photography, was that a number of points were not easily visible because they were positioned behind or close to either ductwork or piping layouts. In all, some 14 photographs were necessary to cover the hundred or so points in this network. Depth-of-field considerations were critical because within any one photograph camera-to-object distances ranged from as little as 1.5 m to as much as 4 m. Through the aid of the STARS simulator, standard errors of close to 0.17 mm were estimated for the targets in the cockpit section. Once again, the distribution of object point precision was quite homogeneous, with no point displaying a standard error value in excess of the tolerance of 0.25 mm.

Positioned on the cockpit window frames were four targets which had previously been surveyed from outside the DF by digital theodolites. The coordinates of these "control" points were established in the tool reference system. When coupled with nine other similarly surveyed points on the walls adjacent to the cargo door, the four targets provided the means to transform the photogrammetric *XYZ* coordinates into the tool reference system, thus providing uniformity between the datum of the CAD database and that of the as-built fixture.

TAIL SECTION

In designing a photogrammetric network for the tail section of the DF, two principal difficulties had to be overcome. The first was the encroachment of the tooling jig into the interior of the structure (Figure 2), with two levels of flooring creating immediate target visibility problems. Compounding this concern was the presence of a number of slanting transverse bulkheads which effectively formed walls that blocked easy access to targets positioned between them. There was less than a metre clearance between the upper floor level and the lower edge of these bulkheads (Figure 7).

Apart from the anticipated concerns of establishing a favorable network geometry in the face of access constraints, one prominent problem in photogrammetrically measuring points in the tail section was how to tie the targets above the level of the upper floor with those below. Although the point field could be treated as two independent target arrays, accuracy, especially in the *Y* (vertical) coordinate, would be enhanced if all points could be treated in a single network. To achieve this tie, it was necessary to capture some highly oblique photographs from stations adjacent to the loft walls on the lower floor. In this way two to three targets per rib in the upper level could be imaged in each photograph, thus providing the necessary overlap between the two levels. This arrangement is illustrated in Figure 7.

Although network design simulation provides the user with a powerful planning tool for a difficult network like that of the tail section, most of the decisions regarding possible camera station locations could only be finalized by inspection at the site. As it turned out, some 40 photographs were required to fully cover the 300-point target array and yield the required *XYZ* coordinate accuracy. Some targets were imaged in as many as ten photographs whereas other, more inaccessible points were only seen from three camera stations. The resulting RMS value of estimated coordinate standard errors of points in this section was 0.16 mm.

PHOTOGRAPHY

One of the prime motivations for utilizing photogrammetry for the C-17 DF was that the acquisition time for the photography would be short. Work on the DF was ongoing and there was a strong desire to minimize interruptions in the normal production schedule. For two of the networks, namely the cockpit and the tail sections, photography was gathered without any interruption to production work. For photography in the mid section, some scaffolding had to be removed from the cargo bay and other scaffolding assemblies were moved back and forth through the mid body area during the photography so as to avoid obstruction.

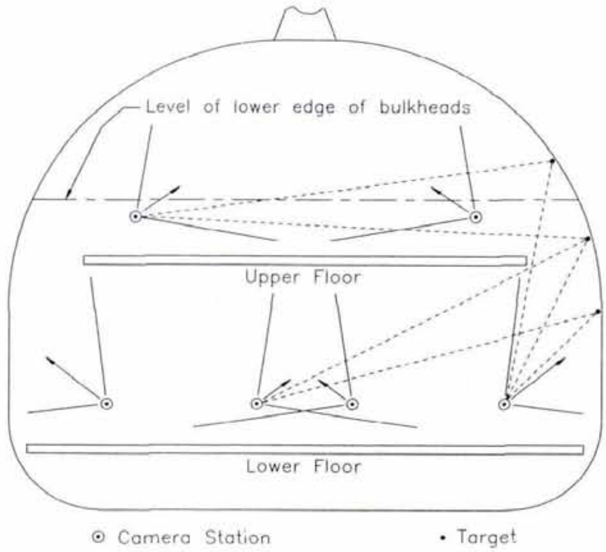

FIG. 7. Camera station geometry necessary to provide a tie between target points above and below the upper floor level of the tooling fixture in the tail section.

The actual time of photography was relatively short, being less than 30 minutes for the cockpit, and just over an hour for each of the mid and tail sections. With the exception of half a dozen or so stations in the open cargo door area, all camera positions were at about 40 cm above the respective floor levels (two levels in the tail section). To facilitate fast operation of the CRC-1 with its base almost on the floor, the camera was mounted on a skateboard arrangement so it could be quickly rolled from station to station. Close to 100 photographs were taken in this fashion in a matter of only a few hours.

The times mentioned for data acquisition do not of course include the time involved in affixing targets. This was a task which consumed a few man-days of work. The target installation did not, however, interrupt routine production work on the DF. Retroreflective stick-on targets were used throughout the networks at all points except those at the four reference hole locations in the cockpit windows where precise tooling targets were employed. The retroflective targets were applied manually utilizing a "U" shaped tool to assist in locating the targets accurately with respect to aircraft fore and aft station locations.

FILM MENSURATION AND DATA REDUCTION

The film was read on a GSI AutoSet-1 automatic video-scanning monocomparator (Brown, 1987) to half-micrometre accuracy. Following the manually assisted measurement of about 30 of the images, all subsequent photographs were measured fully automatically, i.e., the operator was only involved in the set-up phase. In the manual-assist mode it was possible to utilize automatic line following to some extent to measure the targets along each rib. This proved most beneficial in the mid section area. In all, some five working days were required to measure the 92 frames of photography which formed the final three networks.

Because the complete photogrammetric network was separated into three sub-networks at the design and data acquisition stages, it was logical to also perform the data reduction in three phases. Thus, bundle triangulation computations were carried out individually for the cockpit, main cargo, and tail sections. Each of the two outer networks had at least 25 well distributed targets in common with that of the mid section, and thus, following bundle adjustment, all *XYZ* object point coordinates could be transformed into a single reference system.

The first of the networks to be triangulated was that for the main cargo section. Both this network and the other two were processed using a self-calibrating bundle adjustment which incorporated the free-network approach of inner constraints (e.g., Fraser, 1987). With the exception of scale information, which was provided through the provision of two targeted scale tapes, no external control coordinates or other object space constraints were imposed. In the mid section network an RMS value for triangulation misclosures of two micrometres was obtained and the resulting standard errors of *XYZ* object coordinates for the 990 points closely matched those predicted by the design simulation. Similar results were obtained for the 14-station cockpit and 40-station tail section networks, where the RMS misclosures were 1.6 μm and 2.2 μm, respectively. Again, the object point standard errors achieved closely matched the 0.2 mm level anticipated in the simulation stage.

Generally speaking, the CRC-1/AutoSet combination yields triangulation misclosures at the 1-μm level. It is thought that the main reason for the higher than normal image coordinate residuals in this case was the fact that the DF was not fully rigid, and small shape deformations undoubtedly accompanied the moving about and removal of scaffolding assemblies. The small changes in shape during photographic sessions, coupled with extraneous vibration effects from other ongoing structural work, was not of sufficient magnitude, however, to significantly degrade the photogrammetric measurement results.

To bring all *XYZ* coordinates into a uniform reference system, 3D similarity transformations were carried out to transform the coordinates of both the tail and cockpit sections into the datum of the mid section. Each of these transformations involved 25 or more common points, and thus the *XYZ* coordinate residuals could be evaluated against the 0.2-mm overall triangulation accuracy. For the cockpit network, the RMS transformation residuals for *X*, *Y*, and *Z* were 0.25, 0.13, and 0.17 mm, respectively, and for the tail section the corresponding values were 0.26, 0.17, and 0.18 mm. The magnitudes of these coordinate discrepancy values are consistent with the 0.2-mm RMS coordinate standard error produced in the photogrammetric triangulation.

As a result of these two transformations, all object point coordinates were in the reference system of the mid-section network. One task remained and that was to further transform the coordinates into the reference system of the tooling jig and CAD database. This transformation was performed using the 13 points which had been set in by theodolites. Upon transformation, RMS coordinate residuals of 0.22 mm in *X*, 0.16 mm in *Y*, and 0.23 mm in *Z* were obtained. Once again, these values are in line with the estimated 0.2-mm triangulation precision, which in turn can be expressed as a proportional accuracy of 1:215,000 over the length of the DF.

ANALYSIS OF THE MEASURED STRUCTURE

Final results of the photogrammetric inspection were transferred to CAD and compared with engineering design values for each coordinate data point to determine any out of tolerance conditions. In addition to providing data for correction of minor errors due to manufacturing and assembly methods, several significant trends were observed, including effects due to gravity and stress loading. Final results of the coordinate data allowed engineers to modify and optimize the structural design and perform precise adjustment of the airframe structure to meet highest quality standards.

CONCLUDING REMARKS

The data obtained from this application of photogrammetry provided the most comprehensive verification reported to date of overall airframe structure in terms of the size of the object, the number of surveyed points, and the accuracy of the measurements. As new concepts in aircraft structures are developed, advanced methods will be required to verify precision and overall structural conformance to design and manufacturing tolerances. Photogrammetry has proven capable of providing fast, reliable, accurate and economical coordinate measurement data for the dimensional inspection of large aircraft subassemblies and even final airframes.

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BOOK REVIEW

Envisioning Information, by Edward R. Tufte. Graphics Press, Box 430, Cheshire, CT 06410. 126 pages. More than 400 illustrations (most with color) are interwoven with text. Hardbound. 1990. $48.

THE MULTIVARIATE SPATIAL DATA we work with in mapping, geographic information systems, and remote sensing are usually represented as tables or graphics within the "flatland" of the page or computer screen. To help us break from the restrictions of these two-dimensional flatlands, Tufte presents 156 multi-part examples (most using color) that are grouped to promote themes common to excellence in multivariate data representation. He challenges us with examples of information design from numerous disciplines (including many map examples), in familiar and unfamiliar languages, and of both modern and earlier times.

A sampling of topics shows the diversity of examples contained within this slim volume on envisioning information: Galileo's work on both sun spots and the moons of Jupiter (with corresponding representations from the 1980s), restructured periodic tables, visual Pythagorean proofs, the Vietnam Veterans Memorial, pictograph interpretations, systems of dance notation, Japanese calligraphy lessons, maps of birthplaces of Chinese poets, a Swiss topographic map, fishnet surface models of air pollution, meteorological tables, electrocardiograms, electrical activity of dysfunctional brains, graphic and tabular train timetables, a Czechoslovakian air transport timetable, and bumps charting for British rowing contests.

Tufte exhorts us to present complex and multidimensional data in its full richness with graphics that "repay meticulous study." He also encourages us to design for an intelligent reader. By example we become convinced that our own data and our own audiences deserve similarly high levels of respect. In this review I will summarize the keys to excellence in information design that are embedded in his extensive discussions of examples. I hope that this summary encourages investment of your attention in this elegant and inspiring book that has been generating excitement within our discipline.[1]

The first chapter, on *Escaping Flatland*, is an overview that establishes a context for the more specific chapters that follow. Many of Tufte's themes are echoed in the teaching of cartographic design, and he upholds the high-quality map as a standard of excellence for information design. When rich and complex

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[1] Additional reviews in the geographic/cartographic literature are by Monmonier and by Gilmartin (both in *Cartographica*, Spring 1991), by Lai (*The Professional Geographer*, August 1991), and by Detweiler (*Cartographic Perspectives*, Summer 1991)