JAMES B. CASE
Defense Mapping Agency
Washington, DC 20305

Automation in Photogrammetry*

Triangulation mensuration, elevation data extraction, planimetric data extraction, and rectification and orthorectification are now being automated to some degree.

INTRODUCTION

THOMPSON AND MIKHAIL (1976) gave a very thorough rundown on developments in automation from 1972 to 1976 on a country-by-country basis and concluded with a listing of some 15 distinct trends. One of the objectives of this paper is to review some of those trends and see how well they have held up, and to see if any new trends have developed. The functional areas of photogrammetry are examined, present status of automation in those areas is discussed, some of the problem areas in photogrammetry are considered, and future trends in automation in photogrammetry are suggested.

ABSTRACT: *All functional aspects of photogrammetry, i.e., triangulation mensuration, elevation data extraction, planimetric data extraction, and rectification and orthorectification, are now being automated to some degree. Automation extends from computer control of comparators and analog stereo plotters, through the analytical stereoplotters, to orthophoto printers and fully automated correlation equipment. The drive towards automation has been triggered not only by the continuing necessity to reduce costs, but also by the need to generate new products (e.g., DTM, land use, etc.) and to utilize other than conventional mapping photography. These have led, in turn, to the necessity for data editing and data management systems. The trend in the future will be towards the ever-increasing use of digital image processing technology. Examples of several levels of automation in photogrammetry are described.*

The American Heritage Dictionary of the English Language defines automation as "the automatic operation or control of a process, equipment, or a system." Automatic, in turn, is defined as "acting in a manner essentially independent of external influence or control." Realistically, very little of what has been called automation meets that definition. Therefore, that definition will be broadened to encompass those operations which aid the operator, in particular, those operations under some degree of computer control. The functional areas of photogrammetry which will be addressed include mensuration for aerotriangulation, rectification and ortho-rectification, elevation extraction, and planimetric extraction. Image acquisition or photographic processing are not included, nor is so-called automated cartography, i.e., the digitizing and processing of data extracted from graphic sources. In other words, the discussion will be limited to image exploitation.

Why the push for automation? The first concern, of course, is to do the job in a more cost-effective manner, i.e., faster, more accurately, more inexpensively. But other considerations now gaining in importance are the need to utilize new source materials such as Landsat imagery, and the need to produce new products such as the digital terrain matrix (DTM) and digital planimetric data, combined and integrated into so-called "data bases."

AUTOMATION OF PHOTOGRAMMETRIC FUNCTIONS

MENSURATION

Classically, mensuration has served as the initial step in aerotriangulation. Originally, mensuration and aerotriangulation were combined into a single operation in a stereoplotting instrument, the optical or optical/mechanical construction of the in-

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strument itself providing the computation of the aerotriangulation. As analytical triangulation developed, it was found to be more efficient to do the mensuration off line. However, in recent years, with the development of analytical plotters and of stereoplotters with digitizers and with the refinement of independent model triangulation, many organizations have returned to using stereoplotters for aerotriangulation mensuration.

Mensuration normally consists of several steps: (1) the identification of control points and/or the selection of pass points on a photograph, (2) the stereoscopic transfer of those points to the overlapping photographs upon which they appear, and (3) the actual measurement of photograph coordinates of the control points and/or pass points. In off-line mensuration, two different paths have been followed, each with some degree of automation. In the first, point selection and stereo transfer are separated from mensuration the former being performed on a stereo point transfer instrument such as the Wild PUG and the latter on a monocomparator. In the second, point selection, stereo transfer, and mensuration are combined into a single instrument, the stereocomparator. Little has been done to automate the point selection process, although some work has been done to equip point transfer instruments with a coarse coordinate readout which could be used for prepositioning on the monocomparator. A high point in automation of the monocomparator operation was reached with the Automatic Reseau Measuring Equipment or ARME (Roos, 1975). The ARME, when given calibration or approximate values of coordinates of grid intersections (reseaux) on a photograph, drives under computer control to the vicinity of the point and then automatically centers on and measures the point. Similarly, given a star catalog and following manual identification and measurement of at least two stars, the ARME will drive to the vicinity of, center on, and measure the remaining stellar images on a photograph. In the late 1960's attempts were made to automate the stereocomparator process, exemplified by the Automatic Point Transfer Instrument or APTI and the OMI/Bendix TA3/PA. However, these instruments, equipped with correlators, never achieved sufficient accuracy. More recent efforts have concentrated on providing, in the OMI/Bendix TA3/P1 and TA3/P11, operator assistance by performing least-squares relative and absolute orientation, prepositioning, maintaining a y-parallax free model, and allowing for editing of data (Seymour and Whiteside, 1974; Helmering, 1977). Finally, many of these same functions of operator assistance have been incorporated into the analytical plotters for performing mensuration. In particular, with the advent of stable base films and reseau equipped cameras, and because of the high accuracy of the stereocomparators and analytical plotters, it is no longer necessary to mark the points which are to be transferred and measured. The instrument is able to recover the originally selected point based solely on the previously measured coordinates of that point.

RECTIFICATION AND ORTHORECTIFICATION

Rectification is the process of projecting a photograph from its plane to a horizontal plane in order to remove displacements due to tilt. In recent years the definition of rectification has somewhat broadened while, at the same time, rectification has become the most highly automated of photogrammetric functions. The major breakthrough was, of course, the development of differential rectification or orthorectification, in which the rectified photography is further corrected to remove displacements due to relief. And that process has been further refined in that transformations can be made to other than the horizontal plane, producing so called three-dimensional or perspective views.

Rectification began as a straight optical projection with mechanical inversors to maintain the Scheimpflug condition. Some automation has been achieved, with computer control to determine rectifier settings. Initial developments in orthorectification also employed optical projection. However, that projection was limited to a very narrow slit, with the slit being raised or lowered mechanically (i.e., manually by an operator) to profile across the surface of the terrain in the stereo model. The next step towards full automation was the provision of automatic correlation to perform the profiling. And, instead of optical projection, the photography is electronically scanned and projected. Such systems are exemplified chronologically by the Wild B-8 Stereomat, the UNAMACE, the Gestalt Photomapper GPM-2, and the Jena Topomat. These, of course, are online systems. However, in recent years there has been a trend towards off-line systems. Again, most of these systems use optical projection, most are computer controlled, and many are capable of employing profile data, in digital terrain matrix (DTM) form, that are not necessarily collected from the same photography as that from which the orthophoto is being produced. Because they are computer controlled, most of these instruments also are capable of producing stereomates, i.e., an orthophoto into which x-parallax has been introduced such that, when the orthophoto and its stereomate are viewed in stereo, the true terrain relief is presented. Among these off-line orthophoto printers are the Replacement of Photographic Imagery Equipment or RPIE, the Wild Avioplan OR 1, and the Jena Orthophot C. Descriptions of how such off-line systems operate have been given by Scarano and Jeric (1975) and Kraus *et al.* (1979).

The ultimate direction being taken in rectification—a direction which portends the future of automation in all functions of photogrammetry—is that of digital image processing. This involves the direct use of digital imagery, such as that produced by the Landsat multispectral scanner (MSS) or the scanning and digitizing of hardcopy, i.e., photographic, imagery. The imagery, now in picture element (or pixel) form, can then be transformed to any projection or perspective which can be modelled on the computer. Concepts for digital rectification have been given by Konecny (1979) and Keating and Boston (1979) whereas descriptions of actual digital rectification were reported upon by Murai (1978) and Tanaka and Suga (1979). The latter reference is of particular interest because it transforms a vertical perspective—a Landsat MSS image of Mt. Fuji—to a horizontal perspective as viewed from a point on the ground.

Finally, another concept of rectification called digital mono-plotting by Makarovic (1974) and elaborated upon by Masry and McLaren (1979) and Beseniçar (1978) is being implemented at the Defense Mapping Agency as the Extracted Feature Rectification and Processing System (EFRAPS). In this concept, planimetric data are extracted from a single photograph and then digitized. The digitized data are transformed in an iterative fashion into ground coordinates by utilizing digital terrain matrix (DTM) data. The advantages of this concept are that it utilizes inexpensive hardware (assuming that a computer is available) and that it allows for parallel operations, i.e., planimetric data may be extracted before triangulation and elevation data extraction have been completed.

ELEVATION EXTRACTION

Elevation data have traditionally been extracted by an operator utilizing an analog stereoplotter and manually maintaining a floating mark on the surface of the stereo model while traversing the terrain along lines of equal elevation, i.e., contours. The advent of computer assisted analog stereoplotters and analytical stereoplotters has not materially improved this process (the operator must still manually follow the terrain with the floating mark); however, the computer assisted stereoplotters and analytical stereoplotters do offer several advantages over the conventional analog plotters, i.e., they allow for very rapid set-up, they allow for the output of digitized elevation data (DTM), and, particularly in the case of the analytical plotters, they allow for the utilization of unconventional photography and coordinate systems. A thorough description of such systems was given by Dowman (1977).

The big jump in automation of the elevation extraction process came with the development of automatic correlation, described in the previous paragraph on rectification. Although automatic correlation was originally developed mainly to automate the orthophoto production process, it is now coming into its own as a cost/effective means of producing DTM data. This is exemplified by the UNAMACE (Madison, 1975), the Gestalt GPM-2 (Allam, 1978), and the OMI-Bendix AS-11B-X (Scarano and Brumm, 1976). The UNAMACE and GPM-2 employ analog (electronic) correlation technology. However, the AS-11B-X utilizes on-line scanning along epipolar lines and digital correlation of those lines. Another digital on-line correlation concept, called RASTER, has been proposed by Hobrough (1978). However, the future of elevation data extraction, as with rectification, may well lie with off-line digital image processing as described by Panton (1978). The subject of correlation has been recently reviewed by Konecny (1981).

PLANIMETRIC EXTRACTION

The functional area of photogrammetry which has shown itself least amenable to automation is that of planimetric data extraction. As with elevation data extraction, planimetric extraction has been a manual process performed on a stereoplotter. And, again, the advent of computer assisted analog stereoplotters and analytical plotters has not materially aided this process. However, the orthophoto, in at least two disparate ways, has. Specifically, in one instance the orthophoto has become a final product, thus bypassing most, if not all, need for planimetric extraction on a stereoplotter. Examples of this are the many orthophotoquads (orthophotos formated to map sheet lines) produced by the U.S. Geological Survey (Southard, 1978). In the other instance, the orthophoto serves as a base for extraction of planimetric data. In this process, the operator would delineate, on an overlay of the orthophoto, all of the visible planimetric detail. As an aid in interpretation, the operator may use a conventional stereoscope or zoom stereo microscope to view a stereo pair of photographs covering the same area as the orthophoto, and he may then transfer the interpreted detail onto the overlay. Finally, the digital mono-plotting concept, mentioned in the section on rectification, provides another viable technique for planimetric extraction. In particular, the operator can view a stereo pair of photographs under a stereoscope and, simultaneously on an overlay of one of the photographs of the stereopair, he can delineate the planimetric features. The planimetric data on the overlay would then be digitized and transformed to the map projection.

The conventional topographic map is no longer the only product of the planimetric extraction process. With the advent of digital data bases, that process has been expanded to include the collection of land-use data, the performance of wetland inventories, the collection of feature data which can be used to simulate imagery from other sensors such as radar, the performance of terrain analyses to determine off-road trafficability, and so on. These have required the utilization of operators with interpretation skills well beyond those required in the past. In addition, the provision of means for entering feature attribute codes into the data base and the development of the data management systems themselves is required.

As in the other photogrammetric functions, the future of planimetric extraction appears to lie with digital image processing (Bernstein and Ferneyhough, 1975; Andrews, 1977). A great deal of effort is being expended in this area, especially with Landsat MSS imagery, as exemplified by the many journal articles now being published. The real problem in the automation of the planimetric extraction process, as pointed out by Proctor, is "the software problem of persuading correlators not only to match pairs of images but to recognize roads and railways and buildings . . ." (Dowman, 1977b). This problem is being attacked through a new discipline called "image understanding," a part of pattern recognition and artificial intelligence (Baumann, 1979). Interestingly enough, most of the research in this area is being done by electrical engineers and computer scientists, not by photogrammetrists.

INTEGRATED SYSTEMS

The cost/effectiveness of automation is realized most dramatically in systems which combine one or more of the above photogrammetric functions with editing and data base management. Such systems typically are composed of several computer assisted stereoplotters or analytical plotters, a number of interactive displays for the entering of feature attributes and for editing, and a central computer to which the plotters and interactive terminals are linked and which provide for management of the data. A general description of such systems is given by Dowman (1977a) while examples of some systems are given below.

The most ambitious of such systems is the Integrated Photogrammetric Instrumentation Network or IPIN, developed by the Defense Mapping Agency Aerospace Center (DMAAC) in St. Louis for the collection of DTM data from photography. IPIN, which has been well documented by Elphingstone (1978a, 1978b) and others (Fornaro and Deimel, 1978; Kirwin, 1978; Bybee and Bedross, 1978; Elphingstone and Woodford, 1978), consists of the Pooled Analytical Stereoplotter System (PASS), the Automatic Compilation Equipment (ACE, the production version of the AS-11B-X epipolar stereoplotter), the IPIN Postprocessing System, and the IPIN Edit System. PASS consists of AS-11A and AS-11B-1 analytical plotters linked to central ModComp II/45 minicomputers, which act as the data base manager and input/output device for the analytical plotters. The ACE is employed as the high-speed generator of DTM, while the AS-11B-1's and AS-11A's collect DTM in those areas where the ACE correlators will not operate and they collect geomorphic data (ridges and streams) to be used for interpolation. The Postprocessor System manages the IPIN files and handles data flow among all the elements of the IPIN system, it converts ACE epipolar data into the geographic coordinate system, and it interpolates the data into a regular matrix form. The Edit System includes an X-Y plotter and a number of interactive edit stations.

A similar system has been evolving at the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC) since the introduction of the UNAMACE some 15 years ago. At first the UNAMACE produced dropline contours and orthophotos on line. Then, some five years ago (Madison, 1975), the UNAMACEs were directed strictly to the production of DTM, contours being generated off line by computer from the DTM and orthophotos being produced off line by the RPIE (one RPIE can support a number of UNAMACEs). The success of the UNAMACE has resulted in its now being upgraded with modern minicomputers and electronic circuitry. DMAHTC has instituted the same PASS as DMAAC; however, the various collection, processing, and edit systems are not yet directly linked as they are in IPIN. Finally, it should be mentioned that both DMAAC and DMAHTC employ orthophoto (or map) bases with overlays for the extraction of planimetric data and Bausch & Lomb Zoom 240 stereoscopes for the interpretation and analysis of those data.

The U.S. Geological Survey (USGS) and the Surveys and Mapping Branch (Canada) have formed integrated systems based on the Gestalt GPM 2 (Brunson and Olson, 1978; Allam, 1978; Zarzycki, 1978). As with the UNAMACE, the Surveys and Mapping Branch's GPM 2 was acquired for orthophoto production; however, now the major product is the DTM, and the orthophoto is secondary. Planimetric data are collected on computer assisted analog stereoplotters (Wild B8s equipped with an M&S interactive edit system), and drainage data are collected on those same plotters to aid in the interpolation of contours from the DTM. The system is linked to a computer to produce a digital topographic data base. At the USGS DTM are collected with the GPM-2 and both planimetric data and fill-in DTM are collected on a number of computer assisted analog stereoplotters (Kern PG2s and Wild B8s) as well as on analytical stereoplotters (AS-11As and AS-11A-1s).

Another integrated system, the Wetlands Analytical Mapping System or WAMS (Autometric, 1979), has been developed for the U.S. Fish and Wildlife Service. Used exclusively for the collection of planimetric data, it can also perform the mensuration and processing of analytical aerotriangulation. The WAMS consists of the Autometric APPS-IV analytical plotter, display terminals, plotters, and digitizers, all linked to a central computer which manages the WAMS geographic data base.

Finally, an integrated system typical of those in large commercial organizations has been developed by Hunting Surveys Limited (Leatherdale and Kier, 1979). The Hunting digital mapping system consists of Wild A8 stereoplotters linked on line with a central computer. Both elevation data (contours) and planimetry are digitized with this system. However, editing is performed off line on computer generated plots.

The hardware aspects of such integrated systems was recently presented by Petrie (1981).

Problems and Prospects

Data Editing

As the automation of photogrammetry progresses into an era when elevation and planimetry data are produced in digital form and the final product delivered to the user is in digital form, the editing of those data has proved to be the most immediate challenge to the photogrammetrist. In traditional stereo plotting a graphic is produced, which the operator can review and edit visually, either as he plots or after he finishes (or both). As digital systems have developed, most of the editing has remained the same, although a computer-driven plotter would be used to produce the graphic. Such a system has been developed by Hunting Surveys, Inc. (Leatherdale and Kier, 1979.) More sophisticated systems, such as that of the Canadian Surveys and Mapping Branch (Zarzycki, 1979) employ an interactive CRT display to present to the operator a plot of the planimetry as it is being generated in the stereoplotter. Such interactive displays allow for ease in manipulation of data (enlargement or reduction, windowing, etc.) and for on-line editing (deletions, additions) before the data are entered into the data base. However, these systems still require that the operator look away from his stereo display in the instrument in order to view the CRT and make his corrections.

The problem is further exacerbated when editing elevation data, particularly if the data have been collected on one of the automatic correlation instruments (e.g., UNAMACE, AS-11B-X or ACE, Gestalt GPM 2). Again, a computer-driven plotter can be used to produce a graphic, or the elevation data can be displayed on an interactive CRT as contours, profiles, shaded relief, etc. However, because the operator no longer has access to the stereo model, he must resort to a process of "logical" editing; that is, in looking at the contours, profiles, or shaded relief display, he can only surmise that the data "appear" correct or incorrect.

A partial solution to the editing problem, at least for planimetric data, has been implemented as the "position verifier" on the ANAPLOT analytical plotter (Blachut, 1979). A stable film with an electrosensitive coating is placed on a third stage, connected directly to the left photo carrier of the ANAPLOT. As the operator follows details of the terrain with his floating mark, a marking electrode in the form of a stylus produces those same details, in the form of translucent points or lines, on the film on the third stage. These translucent points or lines are projected by a beam splitter into the viewing system of the ANAPLOT and appear superimposed on the stereo model.

The position verifier is not erasable, so that any errors in plotting remain as "clutter," and it cannot be used for editing elevation data. A solution to both of these problems, that of stereo superposition, was proposed by Panton (1978). In his solution, as the planimetry or elevation data are collected in digital form, the photo positions of those data, for each photo of the stereo pair, are computed and the data are projected, by means of CRTs and beam splitters, back into the viewing optics so that the operator sees the data as points or lines superimposed on the stereo model. In the case of a DTM, an array of points would appear to float on the surface of the stereo model. Any points in error would appear to float above or below the surface of the terrain. A similar concept, though presented for map revision rather than data editing, has been suggested by Masry and McLaren (1979). Recently, the U.S. Army Engineer Topographic Laboratories began development for the Defense Mapping Agency of an Elevation Data Edit Terminal (EDET), an analytical plotter incorporating the stereo superposition principal.

Analytical Plotters

When analytical plotters were first introduced in the early 1960s, it was anticipated by many that they were the wave of the future and that every mapping organization would soon have them. However, because of their high cost, and because for the ordinary mapping organization they did not offer any substantial advantages, only the large government agencies and a few universities began to acquire analytical plotters. Then, at the ISP Congress at Helsinki in 1976 nine analytical plotters were exhibited. But they were still expensive, and at the same time a number of conventional stereoplotters were being equipped with computers so that they could perform many of the functions of the analytical plotters. So the era of the analytical plotters still had not arrived. But I believe that it is now here despite what some authors have stated (Schoeler, 1977; Szangolies, 1979). Whole families of analytical plotters have been or are being developed. Some will be very accurate (and still expensive), others will be less accurate but much less costly (and competitive with their counterparts in the conventional analog stereoplotters), and still others will be specialized for specific functions, e.g., elevation extraction (with automatic correlation), planimetric extraction, editing, etc. So this aspect of automation appears to be reaching its maturity.

PLANIMETRIC EXTRACTION

The most elusive area, in terms of full automation, is that of planimetric extraction. The work in image understanding which I mentioned earlier, is impressive, but progress is slow. Similarly, many of the NASA sponsored projects involving the Landsat MSS imagery are leading towards automation of many of the planimetric extraction tasks. However, I tend to feel that we will be fortunate if we see full automation achieved in this century.

CONCLUSIONS

Over the past four years we have seen no major breakthroughs in automation. Rather, there has been a consolidation of earlier gains. This is exemplified by the increasing use of off-line orthophoto printers, of computer assisted analog stereoplotters, and of analytical plotters. The production of digital data has become much more widespread; however, the automated production of DTM is still restricted to the large government agencies. Over the next four years there will be further expansion and consolidation in these areas; further sophistication in the area of editing data, particularly elevation data; and the development of prototype digital image processing systems, at least for orthophoto printing and elevation extraction. However, the development of fully integrated production digital image processing systems is still some ten years off, and the full automation of planimetric extraction may be more than 20 years in the future.

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