ON SYSTEM CONCEPTS FOR DIGITAL AUTOMATION

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ABSTRACT

This paper starts with a review of the merits of digital image photogrammetry, arriving at the conclusion that for mapping purposes its main advantage is its potential to realize efficient automation. With this in mind, standard photogrammetric tasks are evaluated to see how easy or difficult they might be to automate digitally. The result is that all tasks, except feature extraction, can be performed automatically using techniques already in place. Several digital image photogrammetric systems are then outlined to show what capabilities are needed. An evolution from film-based hybrid systems to intrinsically-digital systems is anticipated. Also, the use of digital image photogrammetry in the industrial arena is expected to become a significant new application area. In this evolution, software is seen as an increasingly important system component, capable of becoming the part which is specifically photogrammetric in future processing systems. The paper concludes with an Appendix that attempts to classify both existing and potentially-feasible systems for digital image photogrammetry.

INTRODUCTION

A new technology tends to go through a typical development cycle: Initial discovery and excitement are followed by a lengthy period of research and development until the technology finally begins a rapid, albeit often bumpy, rise towards practical applications and explosive growth. The place where the growth starts is often called the "toe" of the growth curve. Correct detection of the toe is one of the most critical items for successful business use of the new technology. Attempts at business use of the technology too early lead to costly market building and customer education efforts, whereas late entry requires large expenditures to capture a share of an already well-developed, competitive market. Digital image photogrammetry has evolved in this typical pattern. The pioneering work of John Sharp [SHARP 1965] in the early 1960's was followed by the efforts of many researchers during a period of over twenty years. [HELAVA 1972], [CAMBINO 1974], [KREILING 1975], [KONECNY 1978], [PANTON 1978], [KEATING 1979], [CASE 1981], [SARJAKOSKI 1981], [ALBERTZ 1984]. The vigorous activity evident in the last few years may well mark the toe of the growth curve, although this can be ascertained only in retrospect. What seems abundantly clear is that this branch of photogram-metry is worth a close look from technical and scientific points of view.

The status of digital image photogrammetry appears healthy. The basic digital technologies needed to support photogrammetry have progressed dynamically in recent years. Enormous computer power, large memory capacity, and huge mass storage have become not only available, but also affordable.

The variety of special purpose computer chips and boards for image processing and number crunching has increased to an almost incomprehensible level. The display technology has also advanced; time-sharing stereo displays using the liquid crystal polarization principle are available off-the-shelf. With suitable additions, a modern personal computer can be converted to a photogrammetric work station. Simultaneously, business prospects for digital image photogrammetry have expanded dramatically. The key technical element responsible for this is the solid-state camera (CCD and the like). The primary new business area is industrial metrology, mainly gaging and quality control. One can realistically expect photogrammetry to gain a foothold in the lucrative machine vision field through metrology, and expand from there. The prospects should be truly inspirational to all photogrammetrists.

For the reasons above, this seems to be a good time to assess the merits of digital image photogrammetry, and to review its associated technical problems, prospects, and status. An attempt to categorize existing and emerging systems, also appears desirable. The main body of this paper deals with the merits of digital image photogrammetry, how well it handles common photogrammetric tasks and what kinds of systems can be considered state-of-the-art in 1988. An Appendix attached to the paper attempts to classify existing and feasible systems, without passing judgments on their practicality.

EVALUATION OF THE MERITS OF DIGITAL IMAGE PHOTOGRAMMETRY

A new technology becomes successful only if it offers clear advantages. Digital image photogrammetry is no exception; it has to show distinct merits in practical use. Potential advantages may emerge in several areas:

(1) Increased accuracy
(2) Reduced equipment cost
(3) Increased thruput (automation)
(4) Faster availability of results (real-time imaging and processing)
(5) Fast image transmission by electronic means (e.g., SPOT)

These areas are discussed in the following paragraphs.

(1) Increased Accuracy

Practically all images used photogrammetrically today are captured on film. If digital image photogrammetry is to be applied, they must be digitized. The digitizing process can't be completely error free, no matter how carefully done. Errors creep in from optics, mechanics, coordinate referencing, and the fact that pixels have finite dimensions. The effect of pixel size on accuracy is twofold: It limits geometric pointing precision, and it restricts the transfer of information content from film. A digitizing process that in itself would increase accuracy is hard to imagine. At best, digitizing errors can be made insignificant for the application at hand. However, subsequent digital processing may show accuracy gains. Least squares point mensuration, and massive use of reseaus measured automatically, come to mind as possible examples. In general, one must conclude that digitizing of film images tends to decrease, rather than increase, the achievable accuracy.

In the future, most images for photogrammetric use may be captured digitally. Solid-state cameras [GRUEN 1987] are already capable of producing intrinsically digital images today. Their outstanding advantage is that they deliver images in real time; their present shortcoming is low resolution. To cover an area readily captured on film, several solid state cameras or sensors are needed. Therefore, the accuracy comparison becomes indirect; it is embedded into the system design. The comparison is between "apples and oranges", real-time and non-real-time systems. The same accuracy can be reached, but the means and timing considerations differ. However, if the images are inherently digital, the photogrammetric processing should also be digital.

The very topical SPOT [CHEVREL 1981] system produces intrinsically digital images. Without doubt, the trend established by SPOT will continue, and images transmitted from space will become increasingly important in photogrammetry. The metric accuracy potential of such images is under intensive study by many researchers. [DOWMAN 1987], [KONECNY 1987]. Some of that work is done by using film copies of inherently digital images. That reverses the arguments about film digitizing; photogrammetric processing of such images in the digital domain ought to be clearly superior in accuracy.

(2) <u>Reduced Equipment Cost</u>

The question of equipment cost must be approached with caution, keeping in mind the dynamic nature of the computer field. We can predict with a high degree of confidence that the equipment for digital image photogrammetry will eventually be affordable. Our task here is to evaluate the current situation. Clearly, the cost and capabilities of digital equipment are continually changing, and any evaluation of current cost relations is likely to be obsolete in a year, or less. We proceed, nevertheless.

Perhaps surprisingly, the requirements of the human observer emerge as a cost driver in equipment for digital image photogrammetry. The human observer wants a wide field of view, high resolution, freedom of y-parallaxes, ability to scan over large ares, and capabilities to point with a subpixel accuracy. To provide an equivalent of optical performance commonly available in photogrammetric instruments would require a display screen approximately half a meter wide, with 2000x2000 pixel resolution images presented 60 times per second in stereo, and in color.

Electronic displays of these characteristics are not available at this time. However, this level of performance is not absolutely necessary for a usable instrument. There are applications in which monoscopic, black and white, 512x512 pixel (or TV-standard) displays are adequate. Stereo displays of that size are currently available off-the-shelf at reasonable prices, and 1024x1024 displays have been demonstrated. Nevertheless, the requirements set by the human operator remain severe.

Y-parallax-free viewing is easy to take for granted, since it is readily accomplished in optical stereo instruments. In such instruments, the images presented to the observer are rotated to make zero-y-parallax lines parallel to the eye base. In a digital image stereo system the conditions for comfortable viewing are the same, but the images can't be easily rotated relative to the display scan line. For comfortable viewing, the rows of pixels in the digital images must be nearly parallel to the stereo base. Meeting this condition is a serious problem.

The requirement for free roaming over the entire model is not easy to accomplish digitally. The concept is simple: One only needs to change the addresses from which the image data is transferred to the display device. The problem is that memories capable of containing the entire model in stereo are still quite expensive. A data management system for handling a data storage hierarchy is therefore necessary. Such systems are not inexpensive.

Subpixel pointing is another costly requirement. While the digital image can be easily moved by integer pixels on the display, to move it by fractional pixels is difficult. To do it properly, the entire displayed image must be resampled to the required fraction. Again, the concept is simple, but the realization costly.

We are now prompted to ask the question: What does a digital image photogrammetric system that needs a human operator offer to make it superior to the conventional stereo instrument? The answer, at this time, has to be: Very little. However, the equipment cost considerations resulting from the requirements of the human observer make automation look increasingly attractive, since it does not have demanding display requirements. A trade-off can be made between a fancy display system and added computer power for automation purposes. The additional computer power may well be capable of decreasing the need for human intervention to the point where a very simple, low-cost display would suffice.

(3) Increased Thruput (automation)

Increased thruput, if achieved, is clearly a significant advantage. As already indicated above, prospects for achieving significant thruput improvements with a human operator on-line, are not promising. The hope for thruput improvement must be in automation. No definitive statements can be made at this time about the eventual level of benefits achieved via digital automation. However, clear areas of promise exist. In the mapping field, automatic measurement of tie points for aerial triangulation using a hybrid system [HELAVA 1987] is an example. Massive "global correlation" [RAUHALA 1986] and multi-image object space correlation [GRUEN 1985] appear to have great merits. Digital orthophotos have been already produced, and the technique is likely to become economically competitive in the near future, [KREILING 1975], [HORTON 1978/1986] [KONECNY 1978], [KEATING 1979], [GAYDOS 1986], [WIESEL 1985], [ARBIOL 1987].

In the industrial area the prospects are even brighter. The primary reason is that the applications are often well-defined, dealing with relatively few points, and repetitive. Under those circumstances, the system can be made to function completely automatically. In addition, images can be moved "by wire", enabling concentration of automation hardware into a centralized, high performance installation.

(4) Real-Time Imaging

Real-time imaging is already realized for mapping by SPOT, and in various industrial applications [HAGGREN 1984], [FRASER 1986], [EL-HAKIM 1986], [HAGGREN 1987]. In the mapping field, the advantages of real-time imaging are not very significant, since much time-consuming data manipulation is necessary before the maps are in their final form.

This is particularly so when the processing is largely manual. While it is true that from time to time, "quick look" capabilities are of cartographic interest (e.g., in the case of disasters), in general, the real-time aspect of digital imaging does not seem to offer significant advantages in mapping.

In industrial photogrammetry, the situation is much different. Real-time imaging may well be the breakthrough industrial photogrammetry has needed to become a viable technique. In a vast majority of industrial applications the results are needed almost immediately. The need to take, develop, and analyze photographs has been a big impediment for acceptance of photogrammetry (not to say anything about the special skills needed to work the cameras, chemicals, and plotters). Real-time imaging is a powerful advantage for industrial use of digital image photogrammetry, but only if the subsequent photogrammetric processes are equally rapid. Automation appears necessary; manual operation would negate the advantage.

(5) <u>Electronic Image Transmission</u>

Electronic image transmission is certainly a big advantage for bringing images down from a spacecraft [SPOT], or collecting them from different parts of an industrial plant to a centralized processing installation. Eventually, some advantages may emerge for extremely large "map factories" and military uses. However, such expectations are totally speculative at this time.

The results of the review given can be summarized in one sentence: The primary merit of digital image photogrammetry is its potential for efficient automation. To sharpen the conclusion even more: In digital image photogrammetry, manual operation is an antithesis to efficiency; it should be avoided. Digital image photogrammetric systems should be designed to be "automation friendly".

AUTOMATION OF PHOTOGRAMMETRIC TASKS

The success of digital image photogrammetry as a practical technology hinges on its potential to realize effective automation. Its unique power for achieving that success is the virtually open-ended potential of algorithmic sophistication. Probably, almost everything can eventually be done automatically. Our objective in this paper is to assess the difficulties that may be encountered in the automation of common photogrammetric tasks using current techniques.

<u>Interior Orientation</u>

In "classical" film-based photogrammetry, the geometric relationship between an image recorded on film and the "interior" of the camera is lost when the film is spooled ahead in the camera. To re-establish this relationship, an "interior orientation" must be performed. In many digital cameras the sensor remains fixed, and the relationship is not lost. Therefore, no interior orientation is needed; the row and sample numbers of pixels provide a permanent image coordinate system. Interior orientation in those cameras is inherently "automatic". In the case of a line sensor, only one dimensional interior orientation is inherently permanent.

Automatic interior orientation of digitized film images is fundamentally straightforward; the only thing needed is to automatically find the pixel coordinate (row and sample, line and column) values of fiducial marks. This can be done by correlating restored digital images of fiducial marks, or masks representing them, against corresponding images on the digitized photo. These coordinates can then be used, together with calibrated fiducial coordinates, to compute the needed pixel-to-photo transformation. However, interesting practical problems arise. When the photograph is digitized, the fiducial marks get recorded in some arbitrary phase relative to the pixel pattern and the prestored images or masks of fiducials. Consequently, biased correlations may result. This danger can be avoided by measuring the fiducials before digitizing, using a system that actually centers on the marks. Another practical problem is finding the digitized images of fiducial marks in the usually massive data set representing a digitized image. At a minimum, the file header should indicate the approximate locations of the fiducials.

In summary, automation of the interior orientation of digital images is in most cases very simple. The practical problems alluded to above are not serious.

Orientation of Photographs

Automatic orientation of photographs using analytical techniques is today quite common place. These same methods and techniques are directly applicable to digital images, once the orientation points have been measured. Automatic measurement of orientation points is well within the state of the art. Automatic point selection using interest operators or object space analysis is necessary for best results. Hierarchical pull-in capability is imperative for fully automatic operation. Semi-automatic measurement of control points is the most practical approach at this time, even though fully automatic techniques based on stored images of control point have been in use since the ERTS (Landsat) development in the early 1970's. Conceivably, the control point identification problem disappears when the air station coordinates can be determined accurately using the GPS system [ACKERMANN 1986].

In summary, automation of the orientation of digital images is well within the state of the art.

Orthophoto Generation

Generation of digital orthophotographs can be approached using concepts similar to those of conventional orthorectification. An elevation grid (Digital Terrain Model, DTM) of suitable density is first produced. The grid corners are then transformed onto the photograph, and the image information is transformed back to the grid square-by-square using (for example) bilinear transformation and an appropriate resampling scheme. [KONECNY 1978], [KEATING 1979]. In a more ambitious approach, each orthophoto pixel is transformed individually to the digitized photograph, and its density value determined by resampling. The density is then stored to the original orthophoto pixel location. [KREILING 1975], [HORTON 1978]. One can argue that the approaches become identical when the density of the grid is made very high. The practical problem, of course, is how to determine valid elevations at a very small grid interval, let alone at each pixel.

The planimetric accuracy of a digitally-generated orthophoto depends primarily on the accuracy of the elevations assigned to pixels. Conceivably, by using multi-image correlation, an accurate elevation could be measured at each orthophoto pixel (or ground element, "groundel"). A new photogrammetric product, existing only in the digital domain, might emerge; a product that combines an extremely dense DTM and an orthophoto. It might be considered akin to a Geographic Information System data base with information other than density (reflectivity, sensor response) and elevation stored at its groundel cells.

Today's orthophotographs are just that, photographs. They are used in a manner that permits reduced planimetric fidelity, which in turn makes less accurate elevations acceptable. Specifically, the elevations do not have to be true "bare earth" elevations. Rather, the shape of the visible surface should be represented, and fair amounts of generalization and smoothing are tolerable. Consequently, automatic generation of orthophotos in the digital domain is well within the current state of the art. Several significant improvements are also possible within the current state-of-the-art. For example, image enhancements can be applied and individual orthophotos mosaicked virtually ad infinitum. Specific parts of the mosaics can be designated for output and annotated individually. The resulting digital orthophotos can be readily output in photographic form by using drum printers and the like, and displayed in soft copy form on CRT screens.

In summary, generation of orthophotos is well within the state of the art of digital image photogrammetry.

Digital Terrain Model Generation

Digital image photogrammetry is well suited to the production of DTMs. Its main strength is in algorithmic versatility. Theoretically, virtually any algorithm can be used to achieve the required results. The problem is that, at this time, we do not know what needs to be done to get some of the desired results. The "bare earth" DTM is an example. Evidently, some currently unknown Artificial Intelligence (AI) algorithms must be employed to solve that problem. Multi-image and multispectral inputs to the AI processes may be needed before bare earth DTMs can be produced automatically.

Fortunately, a bare earth DTM is not always an absolute requirement. Visible surface representation suffices for orthophoto generation, as described above. Small scale mapping is another example. In that case, effects of terrain coverage can be ignored.

In summary, automatic generation of digital terrain models for some applications is well within the state of the art of digital image photogrammetry. In the most demanding applications, where current knowledge is lacking, digital image photogrammetry offers the best prospects for eventual success in automation.

Feature Extraction

Feature extraction is one of the most time consuming tasks in photogrammetric mapping. The same is probably true for most non-cartographic and industrial applications of photogrammetry. Therefore, automation of this function would be very beneficial.

Unfortunately, no current technology, digital or otherwise, can offer anything even close to full automation of feature extraction. Some semi-automatic "tools", implemented digitally, are beginning to show promise, but are still a long ways from being practical or significant. Eventually, full automation may be achieved, most probably by using digital methods. Digital image photogrammetry is the natural application environment for semi-automatic and fully-automatic techniques, when they mature.

In summary, digital image photogrammetry offers the prospect for semi-automatic and fully-automatic feature extraction, but must currently rely on manual extraction methods. This is a very important point. It means that its full automation potential can't be realized at this time, and that a significant part of the digital image photogrammetry system must be "operator friendly", thus, relatively costly.

CURRENT STATUS

The ultimate digital image photogrammetric system will be a "black box" processor, perhaps intimately connected to the sensor(s), capable of autonomous execution of processes needed to achieve the required results. The ultimate will be reached through evolution; an evolution that at the present time has hardly begun. The evolution will happen step-by-step, needing to overcome a set of obstacles at each step. The major obstacles at the present time are two: The lack of suitable digital cameras, and the inability to automate image interpretation (e.g., for feature extraction). Except for some industrial applications, images must be recorded on film and then digitized. This decreases accuracy and increases costs. The need to have an operator on-line, to do interpretation tasks that require a high-performance human interface, increases operating and equipment costs. Here is a worthy challenge to photogrammetric research institutes: Attack and solve the interpretation problem, even though it's not photogram"metry"!

Much can be accomplished, despite the obstacles. Most of the current prospects seem to be in the industrial area, yet to be explored. In mapping, some progress has been demonstrated, but no wide application can be expected until the advent of a mapping-quality digital camera, or superb digital photointerpretation software.

Some core requirements must be met to make digital image mapping systems feasible using current technologies. The most obvious of these is the ability to digitize film images accurately, economically, and with sufficient resolution. A less obvious, but equally important, requirement is the ability to point and track with subpixel accuracy. If you have to digitized the images with a pixel size commensurate with the required pointing precision in integer pixels, the data volume to be stored, manipulated, and displayed would make the system totally impractical at this time. Fortunately, an operator can measure to a fraction of a pixel; provided, of course, that the system has appropriate capabilities. Thus, larger pixels can be used. [TRINDER 1986] To execute pointing and tracking, the operator needs "operator friendly" xyz controls. A data tablet with an additional z-control has been used successfully. Last, but not least, sufficient data storage, bus speed, input/output channels, and data processing power are essential requirements for a digital image mapping system.

The core requirements can be met by a variety of means. For example, literally dozens of different designs can be proposed to meet the data processing and digitizing needs. Obviously, solid system concepts and careful trade-off studies are essential. System optimization involves very complex issues. In years to come, it presents a worthy challenge to those who produce systems for photogrammetrists to use.

EXAMPLES OF STATE-OF-THE-ART (1988) SYSTEMS

As indicated above, literally dozens of different systems can be designed to meet the needs of digital image photogrammetry. In the following paragraphs, we describe three types of 1988 state-of-the-art systems in generic terms. To avoid last minute updating and possible immediate obsolescence, we have taken a tiny liberty with the definition of "state of the art"; some of the capabilities described may not have been realized, but they "could have been".

Hybrid System

In a hybrid system the images remain stored on film. Parts of the images are digitized "on demand", as needed for processing. Analytical plotters equipped with CCD cameras [ABSCHIER 1979], [WULLSCHLEGER 1986], [PERTL 1984] and the DCCS aerial triangulator [HELAVA 1987] are typical examples. In these systems, interior orientation is necessary; and easy to perform automatically, if desired. Orientation points and tie points are selected automatically (for example, by using interest operators), and found on subsequent photographs using hierarchical pull-in techniques. Blunders are eliminated by performing point cluster analysis, or measuring extra points. Multi-image least squares correlation is used to improve accuracy of point measurements. Measurement of control points, however, requires operator assistance. On-line triangulation of varying degrees of sophistication can be performed using hybrid systems.

Hybrid systems are capable of automatic orthophoto generation. To do that, a visible-surface DTM is collected. While an integrated process of simultaneous DTM collection and orthophoto generation is technically feasible, separation of the two is advisable. The reason is that considerable editing of automatically collected DTM data is nearly always necessary. The orthophoto is generated by area transfer, or pixel-by-pixel transfer. The former is more practical at the present time.

A "bare-earth" DTM can be generated automatically in those areas where terrain coverage and artifacts are minor. Where that is not the case, analysis of residuals after least squares correlation can eventually provide a useful tool for automatically generating a "bare-earth" DTM. However, at the present state of development, a substantial amount of manual editing is necessary in either case.

Feature extraction is done manually, since automatic feature extraction is not yet practical. Manual feature collection capability is inherent in hybrid systems built around analytical plotters. The digitizing capability is superfluous in this mode of feature extraction; it offers no advantages. Monoscopic soft copy display can be an effective alternative to the analytical plotter. Two approaches are attractive. In one, a servo controlled digitizing camera, capable of scanning the input film, is combined with a display.

The operator traces (plots) features with the display cursor, using a data tablet to control the tracing motions. The resulting stream of image coordinates is fed into the system computer, which uses known orientation parameters and the DTM to derive corresponding ground coordinates. In the other one, the operator traces the features directly on a photograph mounted on the data tablet. This approach leads to a low cost device, but accurate tracing is difficult.

Fully Digital System for Mapping

Fully digital systems have no optical-mechanical scanners on line. The images are either intrinsically digital, e.g. SPOT images, or predigitized from film. Minified overview images, e.g. in scales 1:4 and 1:16, are useful; and can be produced easily on-line or off-line. Several different types of digitizers are available. From the photogrammetric point of view, they are not all equally acceptable. For example, some drum scanners have been shown to have significant geometric errors [BOOCHS 1984]. Various electronic and optical imperfections can reduce the inherent accuracy of CCD scanners [BEYER 1987], [DAHLER 1987]. The photogrammetric community must pay attention to metric integrity of digitizers and verify their performance by careful studies. At this writing the author feels most comfortable with well calibrated, comparative-type devices which use calibrated CCD area sensors to digitize the image.

Where and how to store the image data is one of the most serious problems in full-image digital photogrammetry. The volume of digitized image data is very large. Only a few years ago, storage of more than a few full photographs for near real-time access, was utterly impractical. Today, hundreds of digitized photographs can be stored in "juke-boxes" of optical disks. However, a storage hierarchy and associated data management schemes are still necessary and can present problems. Data transfer rates tend to become limiting factors, as the storage capacities and processing speeds increase.

Solutions of photogrammetric tasks using fully digital images are similar to those discussed in connection with hybrid systems. The main differences are in storage and access of images. One area that needs special attention is accurate recovery of interior orientation. Obviously, when the images are inherently digital, no interior orientation is needed. However, when the images are digitized from film, accurate interior orientation must be performed. One way of doing this is to use a comparator-based digitizer. Fiducial marks and reseaus can then be measured accurately, either manually or automatically by performing actual pointing. This permits computation of interior orientation a priority, and digitization in photo coordinates. Another possibility is to scan in digitizer coordinates and recover the interior orientation by correlation on digitized images of fiducial marks and reseaus. The former method is more reliable.

Feature extraction is another area where full image processing differs from hybrid processing. The full image environment is significantly more favorable for the use of semi-automatic and, eventually, fully-automatic feature extraction tools and techniques. Currently, manual extraction is virtually always necessary. For that the operator uses a work station consisting of a computer, display, and disc storage.

Thus, no mechanical photo stage is on-line while the operator collects the features. Alternatively, an orthophoto can be stored on the disc. However, this approach is less general, since orthophotos may not be otherwise needed. In both these cases, the operator traces the features with the display cursor, using a data tablet to control the movements of the cursor. Graphic capabilities to monitor the progress of feature extraction, and to add symbols and lettering, are readily available.

Industrial System

At least three types of systems have been designed for industrial use of digital image photogrammetry. Perhaps the oldest of these is a hybrid system that uses digitized patches of photographs to center on images of retroreflecting targets [FRASER 1986]. The newest is a system consisting of servo driven theodolites equipped with CCD sensors. The sensors are used to aim the theodolites at retroreflecting targets [GOTTWALD 1987]. The justification for considering such a system "photogrammetric" comes from regarding the theodolite, in this configuration, as a "camera". The third type is most genuinely "digital image photogrammetric". [HAGGREN 1987] This system consists of multiple CCD cameras (typically four), video frame grabbers, a host computer, and software. The cameras are synchronized to permit measurement of moving objects. In operation, the system is first calibrated using 15-20 known points in the measurement volume. The resulting transformation includes all orientation elements, lens distortions, etc. Actual measuring is done by projecting a laser beam on the object, extracting the image coordinates of the spot, and using the intersection method and calibration information to determine the three dimensional coordinates of the spot. The measurements happen in near real-time, in a few seconds per point. This capability is extremely important in industrial applications. It may well be the key that opens industrial markets for photogrammetry.

CONCLUDING REMARKS

Digital image photogrammetry is still in its infancy, even though some systems are already in practical use. Rapid progress can be expected, due to the extraordinary technical and commercial vigor of digital technologies in general. Further impetus for rapid progress comes from the emergence of new markets, particularly in the industrial arena. Industrial metrology and quality control offer opportunities for both hybrid and fully digital approaches. The ability to perform measurements in near real-time makes the fully digital system the heavy favorite.

Two impediments hinder the progress of digital image photogrammetry in mapping: Lack of mapping quality digital cameras, and inability to do automatic feature extraction. Both hindrances are serious, but the camera problem may be easier to solve. One can, at least, visualize camera designs whose realization depends "only" on the extension of existing technologies, whereas nobody can show how the feature extraction problem could be solved by straightforward extension of existing technologies. This does not mean that the hindrances present unsolvable problems; partial solutions may be close at hand, and full solutions will be forthcoming eventually. The progress will happen step-by-step, probably starting with automation of triangulation and progressing to DTM and orthophoto generation.

Some semi-automatic tools for feature extraction may be found useful fairly quickly, but full automation is unlikely to become practical in the near future. Progress in automation will be the pacing item for acceptance of digital image photogrammetry. If digital image photogrammetry can't show clear advantages through automation, it will not be economically attractive.

Eventually, digital image photogrammetry will succeed and become the technique to use in mapping as well as in industrial measurements. There will be no need for hardware that's specifically "photogrammetric"; efficient systems can be put together from off-the-shelf parts. The only thing that remains photogrammetric is the software. An interesting prospect for manufacturers of photogrammetric instruments to contemplate!

APPENDIX

CLASSIFICATION OF SYSTEMS FOR DIGITAL IMAGE PHOTOGRAMMETRY

INTRODUCTION

Systems for digital image photogrammetry can be classified into two basic groups:

1. Hybrid systems
2. Intrinsically digital systems

In the classification that follows, the basic groups are divided into subclasses based on functionality. The subclasses are divided further using criteria giving meaningful separation. These criteria vary from subclass to subclass. There exist an enormous number of technical characteristics that could be used for further subdivision. These tend to have less meaningful separation power, and have been listed in some cases as typical "attributes".

Some of the identified classes have conceptual representatives described in literature; some classes have not been described before. Very few classes have actual realizations; some may never be realized, but are conceptually feasible.

1. <u>HYBRID SYSTEMS</u>

Description: Input images on film; image coordinates in micrometers and integer pixels.

Attributes: Pixel size, image processing capabilities.

1.1 ANALYTICAL PLOTTERS WITH AUXILIARY DIGITAL SENSORS

Description: Classical analytical plotter configuration; patches of images digitized as needed.

Attributes: Sensor size, correlation method, etc.

1.1.1 LINE SENSOR

1.1.1.1 WITHOUT VARIABLE SENSOR OPTICS
1.1.1.2 WITH VARIABLE SENSOR OPTICS (ZOOM AND ROTATION)

1.1.2 AREA SENSOR

1.1.2.1 WITHOUT VARIABLE SENSOR OPTICS
1.1.2.2 WITH VARIABLE SENSOR OPTICS

1.2 DIGITAL COMPARATORS

Description: Capable of high-precision sensor positioning; accurately calibrated sensor system; image patches stored.

Attributes: Accuracy, patch size, storage capacity, man/machine interface, etc.

1.2.1 MANUAL POINTING

1.2.1.1 INTEGER PIXEL PRECISION
1.2.1.2 SUBPIXEL PRECISION

1.2.2 AUTOMATIC POINTING

Attributes: Point selection method, correlation method, blunder detection, on-line point positioning, etc.

1.2.2.1 OFF-LINE POINTING
1.2.2.2 ON-LINE POINTING

2. <u>INTRINSICALLY DIGITAL SYSTEMS</u>

Description: Input images (full frames) inherently digital, or predigitized.

Attributes: Pixel size, digitizing format, display refresh rate, plotting (roaming) rate, operating controls, image processing capabilities.

2.1 DIGITAL IMAGE ANALYTICAL PLOTTERS

Description: Operation similar to analytical plotters

Attributes: Display size, geometric refresh rate, display type, resampling method, movable/fixed cursor.

2.1.1 OFF-LINE RECTIFICATION OR DEWARPING

2.1.1.1 INTEGER PIXEL PRECISION
2.1.1.2 SUBPIXEL PRECISION

2.1.2 ON-LINE RECTIFICATION OR DEWARPING

2.1.2.1 INTEGER PIXEL PRECISION
2.1.2.2 SUBPIXEL PRECISION

2.2 DIGITAL IMAGE (ORTHO-)RECTIFIERS (DEWARPERS)

Description: Accepts full frame digital images and associated orientation/dewarping/ DTM data as inputs, produces full frame (ortho-)rectified (dewarped) digital images.

Attributes: Input/output formats, geometric granularity (pixels, facets, etc.), resampling method, pixel size, scan line orientation, speed.

2.2.1 GENERAL PURPOSE COMPUTER SYSTEM

2.2.2 GENERAL PURPOSE IMAGE PROCESSING SYSTEM

2.2.3 PHOTOGRAMMETRIC IMAGE PROCESSING SYSTEM

2.3 DIGITAL IMAGE COMPARATORS

Description: Capable of accepting full frame digital images and performing pointing with subpixel precision.

Attributes: Pointing precision, image storage capacity, access time to different images.

2.3.1 MANUAL POINTING

Attributes: Display type, display size, display rectification (dewarping) method and rate, manual controls.

2.3.2 AUTOMATIC POINTING

Attributes: Point selection method, correlation method, blunder prevention method, controls.

2.4 DIGITAL MONOPLOTTERS

Description: Accept full frame digital images as inputs, permit feature extraction from such images.

Attributes: Roaming ranges, extraction speed.

2.4.1 NO IMAGE RECTIFICATION

Description: Extracted features are transformed from image to ground, images are used without geometric rectification or dewarping.

Attributes: Integer pixel or subpixel precision, on-line or off-line transformation, DTM used or not used.

2.4.1.1 MANUAL EXTRACTION
2.4.1.2 SEMI-AUTOMATIC EXTRACTION
2.4.1.3 AUTOMATIC EXTRACTION

2.4.2 IMAGES (ORTHO-)RECTIFIED (DEWARPED)

Description: Features are extracted from images that are rectified, orthorectified, or dewarped.

Attributes: Integer pixel or subpixel precision, on-line or off-line rectification.

2.4.2.1 MANUAL EXTRACTION
2.4.2.2 SEMI-AUTOMATIC EXTRACTION
2.4.2.3 AUTOMATIC EXTRACTION

2.5 AUTOMATIC DTM EXTRACTORS

Description: Produce DTMs automatically and autonomously (without operator monitoring) over blocks of photographs (one model = small block).

Attributes: Reliability, accuracy, speed, capacity.

2.5.1 GENERAL PURPOSE COMPUTER SYSTEM

2.5.2 SPECIAL PURPOSE PHOTOGRAMMETRIC SYSTEM

2.6 INDUSTRIAL METROLOGY SYSTEMS

Description: Designed specially for industrial ("terrestrial", "close range") measurements.

Attributes: Laser pointing, reflecting target, random point correlation.

2.6.1 OPTICAL AXES FIXED DURING OPERATION

2.6.1.1 FIXED SENSOR(S)

2.6.1.1.1 SINGLE SENSOR
2.6.1.1.2 MULTIPLE SENSORS

2.6.1.2 MOVABLE SENSOR(S)

2.6.1.2.1 SINGLE SENSOR
2.6.1.2.2 MULTIPLE SENSORS

2.6.2 OPTICAL AXES MOVABLE DURING OPERATION

Description: Digital image phototheodolite, or theodolite with digital sensor.

Attributes: Readout accuracy, sensor size, effective focal length, field angle.

2.6.2.1 MANUAL POINTING

2.6.2.2 AUTOMATIC POINTING

Attributes: DC-servos or stepping motors, pointing on targets only or on arbitrary points

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