Precision Evaluations of Digital Imagery for Close-Range Photogrammetric Applications

Mark R. Shortis
Department of Surveying and Land Information, The University of Melbourne, Parkville, 3052, Australia

ABSTRACT: Semiconductor array and vidicon imaging systems are receiving widespread attention for application to close-range photogrammetric measurement. The principal advantages of these systems are automatic image measurement and real time processing for object space data. However, the resolution of currently available systems is such that there are limitations on the achievable precision of object space coordinates, restricting the potential range of applications. This paper reviews current hardware and techniques with the emphasis on improved object space precision. The results of simulations are presented to indicate the potential precision of a number of hardware configurations.

INTRODUCTION

Non-photographic photogrammetry has been in widespread use since the early 1970s when the first Landsat imagery was made available, and satellite remote sensing dominates the science of image analysis. However, the use of digital imagery for photogrammetric metrology predates remote sensing by almost 20 years, as the first attempts at map production using video scanning were made in the 1950s (Rosenberg, 1955). Since those early developments, video systems have been used in a variety of applications, principally orthophotomap production, but also industrial measurement control (Pinkney, 1978), biostereometrics (Real and Fujimoto, 1985), and close-range photogrammetric metrology (Stewart, 1978; Miller *et al*, 1985).

Significant developments in the use of digital imagery for close-range photogrammetric metrology have occurred in the last few years because of technological advances in microelectronics and semiconductors. The catalyst of these developments has been the introduction of low cost, commercially available semiconductor image sensor arrays and image digitizers compatible with personal computers. Although solid state image sensor arrays were first developed as early as 1970 (Amelio *et al.*, 1970), only recently have digital imaging systems based on solid-state arrays reduced in cost to the point where the capital investment and cost-benefit ratio has become acceptable to a broad spectrum of users.

The impetus behind the development of semiconductor array and vidicon based digital imaging systems has been supplied in the most part by machine vision applications. The majority of these applications revolve around real-time or near-real-time optical sensing for quality control, component inspection, and robot control in industrial or production line environments. Speed is the key in these applications as they are intended to replace manual methods for productivity, reliability, and cost considerations. Close-range photogrammetric systems have been developed for similar reasons, and the majority of the research developments have focused on the automation of the photogrammetric process or near-real-time processing of image data using simple stereopairs (El-Hakim, 1986; Wong and Ho, 1986) or a limited number of cameras and a multistation solution (Gruen and Beyer, 1986; Haggrén and Leikas, 1987).

All of the above applications and examples employ *macro* photography, that is, either direct imagery of the object or the scanning of large sections of conventional photographic emulsions. Digital imaging systems have already made a large impact on photogrammetry and surveying using *micro* photography. The prominent example in this field is the automatic comparator, which scans a small portion of a conventional photograph to sub-micrometre precision. However, this paper will explore the potential of macro photography in the context of the precision of close-range photogrammetry.

The potential of semiconductor array and vidicon image sensors is promising for close-range metrology, but in general such digital sensors are unlikely to precipitate the demise of the analog photograph for some time to come. Apart from the requirements of pattern recognition, image analysis, and image correlation which are being subjected to intense research at present, the limiting factors are the resolutions and format sizes of the currently available sensors. The low resolutions and very small formats of commercially available "off-the-shelf" systems has restricted the use of these types of image sensors to applications with low accuracy demands. The most optimistic relative accuracies in the object space, reported by various investigators concentrating on close-range photogrammetric metrology, have been on the order of 1:5,000 to 1:10,000 (Gruen, 1987).

APPLICATION TO PRECISE CLOSE-RANGE METROLOGY

Conventional close-range photogrammetry has had wide application to engineering and industrial metrology tasks with high accuracy demands (Kenefick, 1971; Cooper, 1979; Fraser and Brown, 1986). The combination of factors such as long focal length/large format cameras, high resolution emulsions, retro-targetting, precision image measurement, and sophisticated multistation simulation, adjustment, and analysis procedures has led to object space relative accuracies well in excess of 1:100,000. Realization of this level of accuracy requires, among other things, large numbers of convergent photographs and imaged targets. A typical application may require up to ten camera stations and 100 targets. If measured manually on a mono- or stereo-comparator, precise image observations become a demanding and time consuming task which degrades the cost-effectiveness of the technique.

The demands of precise image observations can be alleviated partially by using a semi-automatic approach provided by back-driven analytical plotters. When suitably programmed, an analytical plotter can control the coarse pointing for each image observation, leaving the operator to control the fine pointing and then continue the sequence. However, this strategy results in productivity savings "only" on the order of 30 percent. A more effective solution is, of course, full automation, provided by automatic comparators based on semiconductor array or vidicon sensors which view a small portion of the conventional photograph (Luhmann, 1986; Robertson, 1986; Brown, 1987). These systems are largely independent of manual operation after an initialization phase, using digital image processing tech-

0099-1112/88/5410–1395$02.25/0

niques to identify and precisely locate the images of targets. When used in conjunction with retro-targets, which give a clean, readily quantifiable image, the time required for the image observations can be drastically reduced.

The negative aspect of the analytical plotter or automatic comparator solutions is the high capital outlay (and the subsequent running cost of a full time operator for analytical plotters), while the positive aspect is the high precision achievable for image observations over a large format area of conventional photography. The characteristics of semiconductor array and vidicon imaging systems are quite the reverse; the capital outlay is relatively low and the subsequent running costs are minimal, while the image observation precision is relatively coarse and restricted to very small format areas of direct digital imagery.

Certainly the current generation of off-the-shelf semiconductor and vidicon image sensors cannot match the combination of large format conventional photography and comparator measurement. Although pattern recognition techniques may effectively improve the low resolution of the image sensors to a level comparable to the precision of manual comparator and analytical plotter observations, the very small formats of the image sensors results in a grave disadvantage in image scale. Furthermore, the calibration of such digital image sensors is a grey area which is also currently under investigation (Burner *et al.*, 1985; Curry *et al.*, 1986; Beyer, 1987).

However, the attraction of using semiconductor array or vidicon imaging systems for precise close-range metrology is the low cost, automatic measurement of target images. The lack of resolution and small format size can be offset to some extent by the use of sophisticated pattern recognition techniques in conjunction with retro-targets, and by a review of multistation network geometries. The aim of this paper is to present a preliminary investigation of the feasibility of the use of semiconductor or vidicon imaging systems for precise close-range photogrammetric measurement. The investigation is specific to the assessment of achievable object space accuracies for such applications as engineering surveillance and industrial metrology.

DIGITAL IMAGING SYSTEMS

Digital imaging systems in use for machine vision and close-range photogrammetric applications are based around four primary components: the image sensor, the image data digitzer, the host computer, and the image analysis software. A comprehensive description of these components is beyond the scope of this paper; however, the issues relevant to the resolution, reliability, and cost of the image capture will be dealt with here. A more detailed description of hardware components and their functions, as well as an extensive list of commercially available image sensors and image data digitizers, can be found in Gruen (1987). Alternatively, the interested reader is directed to the many conference proceedings concerning solid state imagers and machine vision published by SPIE (the International Society for Optical Engineering) and MVA(the Machine Vision Association of the Society of Manufacturing Engineers).

Image Sensors

The choice of an image sensor device is essentially one of two basic types of imaging technology, either a vidicon tube or a semiconductor array camera. Both these types of camera replace a conventional photographic emulsion with an electronic sensor device. Conventional camera optics are retained, typically using 35-mm SLR or 1-inch television lenses.

Vidicon cameras are based on the photoelectrical effect, and there are a number of different versions which use photoemission or photoconductance and solid state technology (Real, 1986). The vidicon sensor detects the amplitude of incident light on a layer of photosensitive material at the end of a vacuum tube by scanning the material with a beam of electrons, resulting in a continuous analog signal. The image data and transferred to an image digitizer by transmitting a series of horizontal scan lines under a strict timing and format regime, governed by synchronization signals. A fixed number of horizontal scan lines are assembled to compose a full frame, and the frame is refreshed at a rate of 25 or 30 times per second (Hz). The full frame is commonly split into two fields of alternate horizontal scan lines, known as the interlace principle. The fields repeat at a rate of 50 or 60 Hz to enable the full screen refresh.

Semiconductor array devices are based on self-scanning solid state silicon chips (Collet, 1985). The array device may be a linear or area (two-dimensional matrix) type, composed of small photosensitive detectors which accumulate a charge proportional to the incident light photons. The detectors may be either photocapacitors, photodiodes, or photoconductors. Each detector corresponds to a picture element (pixel) of the entire frame. A full frame is acquired from a linear array by the physical line-wise scanning of the object, either by moving the whole camera or moving the array sensor within the focal plane of the camera.

There are various versions of these sensors, differentiated by the charge readout scheme. The most common is the charge coupled device (CCD), but there are also charge injection devices and metal oxide semiconductor photodiodes. The latter two are X-Y addressable within the array, while CCDs use a line transmission scheme from the electronic scanning in a similar fashion to vidicon systems. In fact, the preponderance of CCD array types in the commercial market is largely attributed to their direct compatibility with existing video digitizer technology.

Although vidicon cameras have predominated in the past, they are rapidly being replaced by semiconductor array cameras across a broad spectrum of applications. In terms of machine vision and photogrammetric metrology, CCD cameras have the advantages of excellent sensor linearity and stable geometry/radiometry (Curry *et al.*, 1986), large spectral and dynamic ranges, insensitivity to magnetic fields, low power consumption, small size and portability, low cost, and no maintenance. Purely in terms of reliability and calibration geometry for precise photogrammetric metrology, CCD cameras are the preferred option. Linearity and stability problems are associated with even high quality vidicon tube sensors (Burner *et al.*, 1985), due to the internal analog scanning process and external environmental effects.

However, standard vidicon systems have some advantages over off-the-shelf CCD systems. For example, vidicon systems are not prone to the moiré fringe effects which can impair the images produced by some types of CCD. More importantly, standard vidicon systems have an equivalent resolution over a larger format area when compared to the common CCD systems in commercial production.

Resolution and Format Size

Video systems adhere to one of a number of video signal standards which specify the frequency and number of lines per frame. The standard in Australasia (PAL/CCIR) specifies 50 Hz and 625 lines per frame. The horizontal resolution may vary within each transmitted frame, depending on the quality of the vidicon sensor, from as low as 200 to as high as 2000 television lines, with the initial capital outlay on the camera rising accordingly. Medium quality, medium cost vidicon cameras have a typical horizontal resolution of 1000 television lines. The physical size of the detector area of a standard one-inch video tube is approximately 12.7 mm by 9.5 mm. Adopting horizontal and vertical resolutions of 1000 and 625, respectively, leads to an equivalent rectangular pixel of dimension 13 μ by 15 μm.

In contrast, the physical detection area of CCD arrays is significantly smaller. With some variation, the *de facto* standard array size is 8.8 mm by 6.6 mm. The number of detectors in the array can vary considerably, from as few as 128 by 128, to as many as 1320 by 1035 or higher. High resolution CCDs are comensurately more expensive. A mean resolution for "off-the-shelf" CCDs would be approximately 512 by 512 pixels, and cameras with this order of resolution are comparable in price to vidicon cameras. Adopting the standard detector size and mean resolution because they are common to commercially available CCDs and represent a reasonable cost, the inter-pixel spacing or pixel pitch is 17 μm by 13 μm, marginally larger than the equivalent vidicon pixel.

The term pixel pitch is used in preference to the actual size of the detectors in the array because the photo sensitive area is not continuous. The relationship between detector size and pixel is determined by the characteristics of the sensor, as a significant fraction of the area of the array may be non-photosensitive material devoted to charge transfer. Interline transfer CCD arrays have lines of readout registers adjacent to each line of detectors, which may reduce the total photosensitive area by two thirds (Khosla, 1985). Interline transfer CCDs are also more susceptible to moiré fringe effects. Frame transfer CCDs devote a much smaller area to non-photosensitive materials, largely channel stops between detectors, by using an adjacent but separate non-imaging array as a storage area. This approach allows almost continuous detectors of a proportionally larger size (for the same total area) and minimizes moiré effects.

Hence, typical frame transfer CCD and medium quality vidicon cameras have similar resolution characteristics, but the latter have a larger format area. However, the above discussion applies to area array type CCDs, because linear array CCDs have different characteristics and considerations. The number of elements in linear arrays can vary, but arrays with 2048 pixels are commercially available, albeit at a higher capital cost. The pixel pitch in linear arrays is typically on the order of 13 μm, leading to a physical length of approximately 28 mm. The linewise scanning typically traverses a physical distance of 35 mm to accord with the format of a standard 35-mm conventional camera. The step distance in the linewise scanning may be set to equal the pixel pitch, leading to a corresponding 2560 pixels in the perpendicular direction. Therefore, linear array scanning cameras have an equivalent resolution, but over a much larger format area.

However, the geometric reliability of linear array cameras is inherently less because of the mechanical scanning. It is unclear whether non-linearities in the scanning process can be adequately modeled, or indeed whether the non-linearities can be considered to be predominantly systematic, or if they are perhaps random events. There are also stability problems associated with these cameras, and they are commonly used in a laboratory or office environment for the recording of graphic, textual, or display information under controlled conditions. Use of such cameras in engineering or industrial environments would place additional strain on the calibration problem for precise close-range metrology because of the uncertainty of the calibration and the possible necessity of introducing photo-invariant parameters to model the scanning non-linearities.

Any of the three camera types must, of course, be treated as non-metric because the optics and the rigidity of the body shell are essentially equivalent to 35-mm SLR conventional cameras. Reliable and precise results can only be obtained with at least pre- or post-calibration using a test field, or preferably by means of self-calibration. The principal advantage of the CCD area array camera is that the film deformation problems associated with standard non-metric film cameras are not present, as long as the array is stable. In contrast, vidicon and CCD linear array cameras are likely to exhibit electronic or mechanical scanning deficiencies which are analogous to film deformation. Such deficiencies would require adequate modeling by block- or photo-invariant parameters to achieve the optimum precision and reliability. Vidicon sensors in particular may require sophisticated error models to compensate for short term variations to the calibration. Although the potential image precision of this sensor type is comparable to the CCD sensor, systematic effects are likely to degrade the reliability of vidicon based systems.

Due to the physically solid image plane, CCD area array, vidicon, and perhaps CCD linear array cameras should also be largely free of effects similar to film unflatness variation, which are a characteristic of conventional non-metric cameras. The orientation and shape of the image plane can be modeled by an appropriate test range calibration and included as a constant correction factor. However, the influence of operating conditions and the external environment on the stability of sensor scanning and flatness has not yet been thoroughly investigated. A great deal more research is necessary before procedures and models for the geometric and radiometric calibration of these cameras are confidently established.

Image Data Digitizers

Having established the resolution and format characteristics of the readily available digital image sensors, the image data must be acquired for image measurement and the subsequent photogrammetric computations. This task is accomplished by an image data digitizer. Commonly known as a frame grabber, this device accepts an analog or digital signal from the sensor and allows the host computer access to the data.

The majority of frame grabbers accept video information as an analog signal in one or more of the standard video formats, and convert the image intensity into digital information using one or more analog-to-digital convertors. Real time applications require frame grabbers which are fast and have a large onboard memory to store and transfer each image at video rates. This type is commonly used with area CCDs and vidicon sensors. Linear CCDs use non-standard slow scan controllers as the data acquisition device, because the image sensor is not intended for use at video rates and the large number of pixels per frame would require a prohibitively high data transmission rate.

The frame grabber has a resolution which is quite independent of the sensor resolution, and a mismatch has obvious consequences. To preserve the spatial resolution of the original data source, the frame grabber must have an equal or higher resolution of digitization. Use of a frame grabber with a lower resolution than the sensor will result in a degradation of the acquired image. Digitizing at a higher resolution will, of course, not improve the spatial resolution of the sensor data, and this effective resampling may have other consequences. Common resolution values for frame grabbers are 512 by 512 or 1024 by 1024. Slow scan controllers are generally adjustable to suit a variety of input devices and scan speeds.

Each pixel is digitized from the analog signal to an intensity precision or grey value resolution indicated by a number of bits. Bit values can vary from 6 to 16, but 8 bits is the norm. An 8-bit intensity per pixel corresponds to 256 grey values or shades of grey. True or limited color can be obtained by three simultaneous inputs and a color vidicon or CCD camera, or single inputs using color filters and monochrome cameras.

In the context of close-range photogrammetric surveys for engineering surveillance and industrial metrology, real time processing, a high number of grey levels per pixel, and color are not essential. Considering that most applications are static rather than dynamic, and retro-targets or some other well defined target type are likely to be used, monochrome data with perhaps 32 to 64 grey values should be sufficient. The main advantage is a decrease in the cost of both the camera and the image data digitizer, particularly with regard to image digitizers without real-time image processing capabilities. A high number of grey values per pixel will improve the pattern recognition accuracy for image positions, but in the final analysis the object space accuracy is primarily dependent on the sensor resolution.

Host Computer and Image Analysis Software

Image digitisers commercially available are compatible with a wide range of microcomputers, and IBM compatibles and VME bus based host systems are the market leaders. Image analysis software packages are many and varied, and packages are often bundled with image digitizers. The majority of packages are available in a minimum form as libraries of routines callable from high level computer langauges, or at a higher cost as menu driven, "user-friendly" programs. The functions available range from the simple addition and subtraction of images to sophisticated fast Fourier transforms. Even the most basic of these packages would provide sufficient routines to allow rudimentary image processing to enable the location of the images of discrete targets. A simple threshold and weighted centroid algorithm suffices to give sub-pixel accuracy for image locations when retro-targetting, or some other type of well-defined discrete target, is used.

CAMERA CONFIGURATIONS

The camera configurations for the network simulation tests are shown in Table 1. The table shows the adopted format, focal length, and image location precisions for the three types of image sensors discussed above, plus the corresponding data for two conventional cameras, the Zeiss Jena UMK and the Geodetic Services CRC-1. These latter two cameras are included as they will be used as a basis for a comparison of the results.

The formats of the three digital sensor cameras have been adopted in accordance with the discussion in the previous section, while the focal lengths have been adopted to closely match the format-to-focal-length ratio of the conventional cameras, because there will be direct comparisons made in the results. The choice of a focal length for the digital sensor cameras is less important than it may appear to be at first sight. The availability of short focal length and zoom lenses allows any object field to fill the frame from any reasonable range, leading to a relatively constant image scale. A change in the focal length could be compensated by a change in the camera to object distances in any simulated network, without influencing the geometry/shape of the network or the object space precision. The short focal lengths are preferable, for the sake of the simulation, so that the geometry is unchanged from that used with the conventional cameras. In practice this may not be desirable if there is a dependence between short focal lengths and calibration stability.

The image location precisions for the digital sensor cameras are derived from the pixel sizes discussed in the preceding section combined with a typical sub-pixel target recognition precision of ± 0.1. This figure presupposes that the targets will be sized to span a few pixels at minimum and that an adequate pattern recognition algorithm is available to determine the target image locations. Thresholding alone can readily achieve an image location precision of ± 0.4 pixels (Wong and Ho, 1986), while a precision of ± 0.3 should be readily achievable with simple target recognition algorithms (Torlegård, 1987). However, various authors have reported precisions of ±0.2 pixels or less (Ackerman and Schneider, 1986; Burner *et al.*, 1987; Curry *et al.*, 1986; El-Hakim, 1986; Luhmann, 1986; Trinder, 1987) when using well-defined, discrete targets. Precisions of ±0.01 pixels have been reported for discrete targets using a pre-calibration of the radiometric characteristics of a CCD sensor (Stanton *et al.*, 1987), so a level of precision of ±0.1 pixels would seem readily achievable.

The image location precisions for the conventional cameras are derived from experience using a stereocomparator with a repeatibility of 2 to 3 μm and three to four rounds of image measurements. This represents the achievable image location precision for manual measurement using any of a broad class of instruments embracing monocomparators, stereocomparators, and analytical plotters. Automatic comparators can achieve a significantly better image location precision, but they are excluded from consideration in the following simulations because of their relative rarity and specialized nature. Certainly the vast majority of photogrammetric practitioners would have regular access to a comparator or analytical plotter, while relatively few would have access to an automatic comparator. Further, if an automatic comparator is accessible, then it is unlikely that an alternative would be sought on the grounds of improving the achievable precision and minimizing the processing delay alone.

The figures in brackets in Table 1 represent the equivalent precisions for the conventional photographs if they are scanned by a linear array CCD camera with a 2048 pixel array. Again, a suitable target size and a pattern recognition algorithm with a precision of ±0.1 pixels is assumed. Linear array scanning has been used for direct photography of small objects for close-range applications (Murai *et al.*, 1986), but scanning of conventional photography for close-range applications has not been reported. The assumption which must be made is that the linear array camera can be pre-calibrated for lens distortions, array "deformations," and scanning non-linearities, and that the calibration is stable to acceptable limits. The fiducial marks or reseau of the conventional photography can be used to transform the scanned images into the camera coordinate system for each frame processed in this way.

In all cases the pattern recognition would be facilitated by the use of retro-targets to utilize the clean, discrete images produced by such targets. Retro-targets can be used in virtually any lighting conditions and their use is not restricted to laboratory or controlled lighting environments. Some experimental work has already been carried out to confirm this supposition, using a vidicon camera and a constant light source rather than a flash or strobe (Shortis, 1988).

Further assumptions used in the following simulations are that suitable software is available to carry out target identification and correlation for each frame and between frames, and that each camera has undergone a pre-calibration using an appropriate test field. The latter consideration is not essential, but simply facilitates the target identification/correlation and the subsequent self-calibrating bundle adjustment processing.

Table 1. Digital Sensor and Conventional Camera Characteristics.

Camera	Format (mm) x	Format (mm) y	Focal Length (mm)	Image Precision (μm) x	Image Precision (μm) y
Vidicon	12.7	9.5	9.0	1.3	1.5
CCD area (512×512)	8.8	6.6	6.0	1.7	1.3
CCD linear (2048×1)	35.0	28.0	25.0	1.3	1.3
UMK	160.0	115.0	100.0	1.6 (8.0)	1.6 (8.0)
CRC-1	230.0	230.0	240.0	1.6 (11.0)	1.6 (11.0)

SIMULATION STUDIES

Two examples of recent applications of close-range analytical photogrammetry to industrial metrology and engineering surveillance were used to test the various camera configurations by simulation. The first is the measurement of the surface of a 4-metre diameter microwave telecommunications antenna (Figure 1). The antenna was orginally measured using a Zeiss Jena UMK camera with a 100-mm focal length and stereocomparator observations of monochrome glass plates, realizing a relative

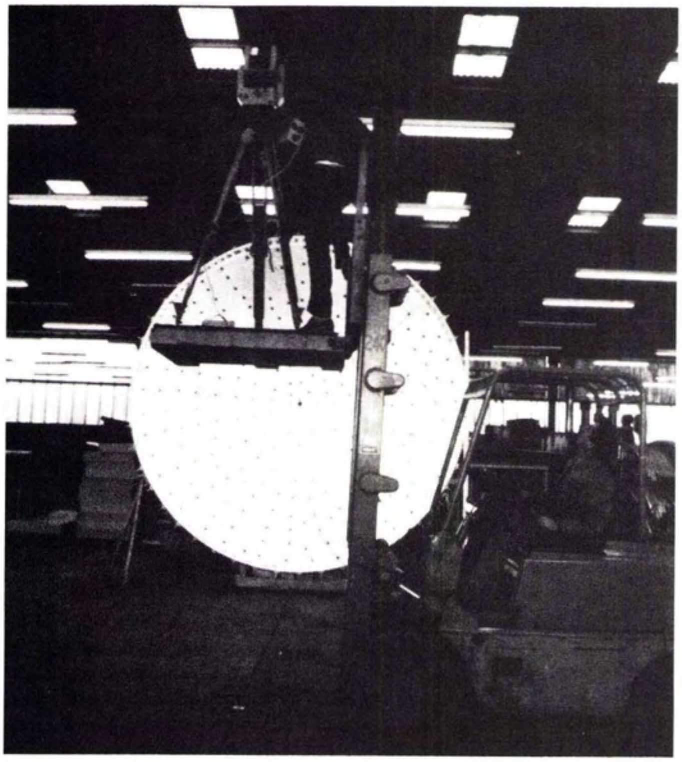

FIG. 1. Microwave antenna.

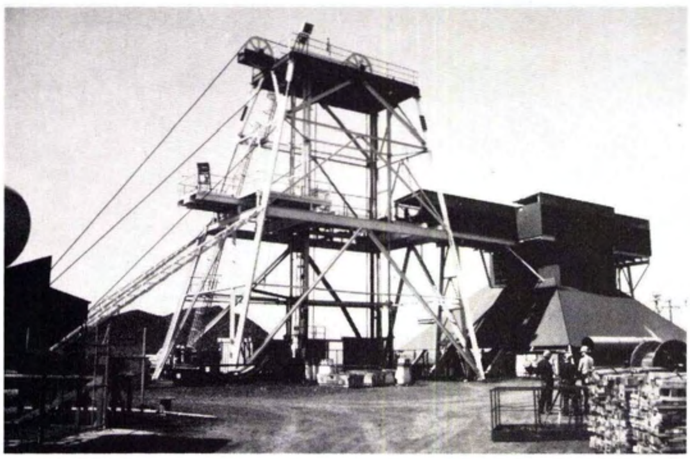

FIG. 2. Head frame structure.

accuracy in the object space of 1:44,000 (Shortis, 1986). The intention of the photogrammetric measurement was the detection of departures of the manufactured surface from the design surface. The second example used is the measurement of a head frame structure above a shaft access to a sewer tunnel under construction (Figure 2). The head frame was originally measured using a Geodetic Services CRC-1 camera with a 240-mm focal length and stereocomparator observations of monochrome film, realizing a relative accuracy of 1:79,000 (Shortis, 1987). In this case the intention is to carry out a long term surveillance program to monitor deformations of the structure.

Both the antenna and the head frame were signaled with discrete targets, the former with 200 self-adhesive cross bar targets and ambient light, the latter with 75 circular retro-targets and a lamp head flash unit. The targets on the antenna were suitable for digital image processing because the antenna was mounted inside a factory in controlled lighting conditions, and the targets showed good contrast against the surface. In terms of the simulation, circular targets and/or retro-targets could have been used to facilitate the image analysis.

The network simulation studies were carried out using a close-range bundle adjustment program employing the collinearity equations with a comprehensive set of additional parameters, known as TBO (Earls, 1983). Interior orientation elements (principal point position, focal length, and radial and decentring distortions) were carried as mildly constrained unknowns in every case, because pre-calibration of each camera configuration had been assumed. A minimally constrained network was used in all cases by explicitly fixing seven coordinates in the target array. Although this will not give the minimum trace of the derived object space coordinates, which could be obtained using a generalized inverse or internal constraints, relative comparisons of results are of importance here.

MICROWAVE ANTENNA SIMULATION RESULTS

The results of the simulations for the microwave antenna are shown in Table 2 and 3. Five camera configurations, with their associated formats, focal lengths, and image precisions, were used; direct photography with the UMK, CCD area, and vidicon cameras, and one case of indirect photography by scanning the conventional UMK photographs with the CCD linear camera.

Table 2 shows the results for each camera when used with four camera stations equally spaced around the rim of the antenna and a convergence angle of 70° (Fraser, 1986). The network geometry used here is similar to that of the original application. The object space precisions and relative accuracies show a trend which is predictable from the characteristics of each imaging system. Using four camera stations, only the conventional UMK photograph would obtain an acceptable object space precision with respect to the original surface tolerance specification of ± 0.25 mm (which corresponds to a relative accuracy of 1:16,000). The scanned UMK photography could achieve the specified tolerance with an additional one or two camera stations around the rim.

The target sizes given in Table 2 are based on a span diameter of five pixels for the digital sensors and 100 μm in the image for the conventional photography. It is worthy of note that the target sizes required for the CCD area and vidicon cameras would result in significant errors in the surface heights of the target

TABLE 2. RESULTS OF SIMULATIONS FOR THE MICROWAVE ANTENNA—FOUR CAMERA STATIONS.

	Object Space Precision (mm)				
Camera	x	y	z	Relative Accuracy	Target Size (mm)
UMK Conventional	0.10	0.11	0.09	1:42,000	4
CCD Area	0.65	1.09	0.66	1:5,000	50
Vidicon	0.44	0.71	0.43	1:7,600	30
UMK Scanned	0.22	0.36	0.21	1:13,400	16

TABLE 3. RESULTS OF SIMULATIONS FOR THE MICROWAVE ANTENNA—MANY CAMERA STATIONS.

		Object Space Precision (mm)			
Camera	Stations	x	y	z	Relative Accuracy
CCD Area	12	0.39	0.60	0.38	1:8,800
	36	0.23	0.35	0.22	1:15,000
Vidicon	12	0.25	0.42	0.25	1:13,000
	36	0.15	0.24	0.15	1:22,000

centers, due to the surface curvature, for targets near the rim of the antenna. Compensation would have to be made for this phenomenon at the image analysis stage.

Improvement in the object space precision achieved by direct photography with the digital sensor cameras can be obtained from simply increasing the number of camera stations. There are little or no consequences to the image measurement of many more frames; in fact, the only real consequences are increases in the necessary time for the field data acquisition and the subsequent photogrammetric computations. Accordingly, Table 3 presents results for networks with 12 and 36 camera stations for the CCD area and vidicon sensors. The 12-station network has the same geometry as the four-station network, while the 36-station network consists of three groups of 12 camera stations (each equally spaced around the rim) with convergence angles of 60°, 70°, and 80°. The convergence is limited to 80° to avoid the possibilities of retro-target response fall off and the influence of narrow, elliptical target images on the pattern recognition.

The results shown in Table 3, while encouraging, show a predictable trend of improvement which is proportional to the square root of the number of camera stations, and therefore the number of measurements. However, the object space precisions for the two sensors and the 36-station networks are now acceptable, or virtually acceptable in the case of the CCD, in terms of the surface tolerance specification. It must be emphasized that the additional observations are acquired at little extra cost and that the reliability of the derived target coordinates would be extraordinary (there would be approximately 14,000 redundancies in the 36-station networks).

HEAD FRAME SIMULATION RESULTS

The results of the simulations for the head frame are shown in Table 4. Five camera configurations were used; direct photography with CRC-1, CCD area and vidicon cameras, and four cases of indirect photography by scanning the conventional CRC-1 photographs with the CCD linear camera.

The first four entries in Table 4 use a convergent network of five camera stations opposite the face of the head frame, again to accord with the original application. The head frame is approximately 20 m high and 25 m wide, with an average depth of 9 m. The camera stations form a vertical rectangle, with a center point, at a distance of 25 m (a crane basket was used to position the camera). Two frames were used from the exposures at each station. The retro-targets (not visible in Figure 2) are well distributed throughout the head frame. The specified tolerance for the target precisions was set at ±0.5 mm, corresponding to a relative accuracy of 1:53,000.

The object space precisions and relative accuracies for the ten photograph cases again show a predictable trend. It is evident that the two small format/short focal length digital sensors are incapable of producing viable results for this case of engineering surveillance. The target sizes required to produce recognizable images are also prohibitively large, and this problem alone would rule out the use of such cameras.

TABLE 4. RESULTS OF SIMULATIONS FOR THE HEAD FRAME.

Camera	Photographs	Object Space Precision (mm) x	y	z	Relative Accuracy	Target Size (mm)
CRC-1 Conventional	10	0.12	0.22	0.12	1:170,000	10
CCD Area	10	4.1	8.0	4.2	1:4,800	310
Vidicon	10	2.6	5.0	2.7	1:7,600	190
CRC-1 Scanned (1)	10	0.8	1.5	0.8	1:25,000	60
CRC-1 Scanned (9)	10	0.27	0.51	0.27	1:74,000	20
CRC-1 Scanned (1)	30	0.5	1.0	0.6	1:37,000	60
CRC-1 Scanned (9)	30	0.15	0.35	0.15	1:114,000	20

The scanned CRC-1 photography is approaching the desirable level of precision, and the result can be augmented by a similar strategy to that used for the microwave antenna. In the case of the head frame, a network of 30 single-exposure camera stations is proposed. The 30-station network composes a rectangular array of five horizontal rows of six camera stations. The result of this simulation, shown in the second last line in Table 4, however still falls short of the specified tolerance, and it is unlikely that this result could be greatly improved by further variation of the network geometry.

The only remaining strategy is the approach taken by Luhmann (1986). Instead of scanning the entire frame of the CRC-1, an appropriate number of portions of the frame are scanned to reduce the effective pixel size. For this particular set of circumstances, a three by three matrix of scans is necessary, leading to nine sub-frames with an image location precision of ±3.5 μm. Each of these nine sub-frames can be conveniently transformed using the five reseau points which would be imaged, and mathematically assembled to effectively form a full CRC-1 frame. In practice, only the reseau and target image locations within each sub-frame would be carried forward, which is in accord with the Luhmann strategy.

The results for this method are shown in Table 4, and although the precisions would undoubtedly be degraded by propagation of error from the additional processing, the results achieved do meet the tolerance specification with ease. However, the sub-frame scanning, although less costly than manual observation on a comparator or analytical plotter, would be a time consuming and tedious process.

CONCLUSIONS

Digital image sensor cameras can be applied to engineering surveillance and industrial metrology applications of close-range photogrammetry. However, in order to augment the object space precision, additional effort must be undertaken in the field or in the laboratory to acquire a significantly greater number of images than the approach normally adopted for conventional photography. The outstanding advantage of digital image sensors is the minimal cost of the "observation" of target images, especially where retro-targetting is utilized to control the image characteristics.

The commercially available digital image sensors based on CCD area arrays or vidicon sensors are limited in their application for direct photography of small objects for industrial metrology. CCD linear arrays show some feasibility for engineering surveillance applications, due to their higher image resolution, by means of scanning of conventional photography. The uncertainty of the scanning process is yet to be quantified and the requirement for sub-frame scanning complicates the procedures, but nevertheless the approach is still feasible.

Periodic reappraisals of direct and indirect photography using CCD and vidicon sensors will be demanded by advances in hardware and as pattern recognition algorithms are improved by further research. For example, CCD linear arrays of 4096 pixels have been recently released onto the commercial market. Of greater interest are CCD area arrays with 2048 by 2048 pixels which have been manufactured and used for scientific applications (Blouke *et al.*, 1987). A format of 55.3 mm by 55.3 mm and a pixel pitch of 27 μm, combined with a better sub-pixel image location precision, would substantially improve the achievable object space precision. When this type of sensor is commercially available at an acceptable capital outlay, it will find application to a wide range of close-range photogrammetric measurement tasks, including industrial metrology and engineering surveillance.

REFERENCES

Ackerman, F., and W. Schneider, 1986. High Precision Aerial Triangulation with Point Transfer by Digital Image Correlation. *Proceedings, International Society for Photogrammetry and Remote Sensing Commission 3 InterCongress Symposium*, Rovaniemi, Finland, pp. 18–27.

Amelio, G. F., M. F., Tompsett, and G. E. Smith, 1970. Experimental Verification of the Charge Coupled Device Concept. *Bell Systems Technical Journal*, Volume 49, April, 1970.

Beyer, H. A., 1987. Some Aspects of the Geometric Calibration of CCD Cameras. *Proceedings, International Society for Photogrammetry and Remote Sensing Intercommission Conference on the Fast Processing of Photogrammetric Data*, Interlaken, Switzerland, pp. 68–81.

Blouke, M. M. B. Corrie, D. L. Heidtmann, F. H. Yang, M. Winzenread, M. L. Lust, H. H. Marsh, J. R. Janesick, 1987. Large Format, High Resolution Image Sensors. *Optical Engineering*, 26(9):837–843.

Brown, D. C., 1987. AutoSet, An Automated Monocomparator Optimized for Industrial Photogrammetry. Presented Paper, International Conference and Workshop on Analytical Instrumentation, Phoenix, 16 p.

Burner, A. W., W. L. Snow, and W. K. Goad, 1985. Close-Range Photogrammetry with Video Cameras. *Proceedings, 51st American Society of Photogrammetry Annual Meeting*, Washington, D.C., pp. 62–77.

Burner, A. W., W. L. Snow, W. K. Goad, and B. A. Childers, 1987. A Digital Video Model Deformation System. *Proceedings, International Congress on Instrumentation in Aerospace Simulation*, Williamsburg, Virginia, pp. 210–220.

Collet, M. G., 1985. Solid State Image Sensors. *Solid State Imagers and Their Applications*, SPIE Proceedings Volume 591, Cannes, France, pp. 82–93.

Cooper, M. A. R., 1979. Analytical Photogrammetry in Engineering: Three Feasibility Studies. *Photogrammetric Record*, 9(53):601–617.

Curry, S., S. Baumrind, and J. M. Anderson, 1986. Calibration of an Array Camera. *Photogrammetric Engineering and Remote Sensing*, 52(5):627–636.

Earls, C. J., 1983. Accuracy Potential of a System for Analytical Close Range Photogrammetry. *Photogrammetric Record*, 11(62):169–182.

El-Hakim, S. F., 1986. Real-Time Image Metrology with CCD Cameras. *Photogrammetric Engineering and Remote Sensing*, 52(11):1757–1766.

Fraser, C. S., 1986. Microwave Antenna Measurement. *Photogrammetric Engineering and Remote Sensing*, 52(10):1627–1635.

Fraser, C. S., and D. C. Brown, 1986. Industrial Photogrammetry: New Developments and Recent Applications. *Photogrammetric Record*, 12(68):197–217,

Gruen, A., 1987. Towards Real Time Photogrammetry. Presented Paper, 41st Photogrammetric Week, Stuttgart, University of Stuttgart, F.R.G., 33 p.

Gruen, A., and H. A. Beyer, 1986. Real Time Photogrammetry at the Digital Photogrammetric Station (DIPS) of ETH Zurich. Presented Paper, International Society for Photogrammetry and Remote Sensing Commission 5 InterCongress Symposium, Ottawa, Canada, 14 p.

Haggrén, H., and E. Leikas, 1987. Mapvision: The Photogrammetric Machine Vision System. *Photogrammetric Engineering and Remote Sensing*, 53(8):1103–1108.

Kenefick, J. F., 1971. Ultra-Precise Analytics. *Photogrammetric Engineering*, 37(11):1167–1187.

Khosla, R.P., 1985. Solid State Imager Applications at Kodak. *Solid State Imagers and Their Applications*, SPIE Proceedings Volume 591, Cannes, France, pp. 46–53.

Luhmann, T., 1986. Automatic Point Determination in a Reseau-Scanning System. *Proceedings, International Society for Photogrammetry and Remote Sensing Commission 5 InterCongress Symposium*, Ottawa, Canada, pp. 400–408.

Miller, J. B., R. S., Pappa, M. L. Brumfield, and R. R. Adams, 1985. Measurement of Orbital Dynamics of the OAST-1 Solar Array Using Recorded Video Images. Presented Paper, 36th International Astronautical Congress, Stockholm, Sweden, 19 p.

Murai, S., F. Otomo, and H. Ohtani, 1986. Automated Three Dimensional Measurement Using Stereo CCD Cameras in the Application to Close Range Photogrammetry. *Proceedings, International Society for Photogrammetry and Remote Sensing Commission 5 InterCongress Symposium*, Ottawa, Canada, pp. 409–413.

Pinkney, H. F. L., 1978. Theory and Development of an Online 30Hz Video Photogrammetry System for Real Time Three Dimensional Control. *Proceedings, International Society for Photogrammetry Commission 5 InterCongress Symposium*, Stockholm, Sweden, 39 p.

Real, R. R., 1986. Components for Video-Based Photogrammetry of Dynamic Processes. *Proceedings, International Society for Photogrammetry and Remote Sensing Commission 5 InterCongress Symposium*, Ottawa, Canada, pp. 363–373.

Real, R. R., and Y. Fujimoto, 1985. Stereo Image Transfer System with Fast Digital Video Processors and Merged Graphics Display. *Proceedings, 51st American Society of Photogrammetry Annual Meeting*, Washington, D.C., pp. 272–283.

Robertson, G., 1986. Test of Photogrammetric Accuracy for Mensuration of Aerospace Tooling. *Proceedings, International Society for Photogrammetry and Remote Sensing Commission 5 InterCongress Symposium*, Ottawa, Canada, pp. 232–240.

Rosenberg, P., 1955. Information Theory and Electronic Photogrammetry. *Photogrammetric Engineering*, 21(4):543–555.

Shortis, M. R., 1986. Close Range Photogrammetric Measurements for Structural Monitoring, Deformation Surveys and Engineering Surveillance. *Australian Journal of Geodesy, Photogrammetry and Surveying*, 45:55–64.

———, 1987. Precise Monitoring of Large Engineering Structures Using Close Range Photogrammetry. *Proceedings, Symposium on the Applications of Close Range Photogrammetry*, University of Melbourne, Australia, pp. 58–75.

———, 1988. *Dynamic Photogrammetry Development Project Interim Report*. Department of Surveying and Land Information Report to the Aeronautical Research Laboratories, January 1988, 29 p.

Stanton, R. H., J. W. Alexander, E. W. Dennison, T. A. Glavich, and L. F. Hovland, 1987. Optical Tracking Using Charge-Coupled Devices. *Optical Engineering*, 26(9):930–938.

Stewart, P. A. E., 1978. The Application of Close Range X-Ray Photogrammetry to the Study of Dynamic Gas Turbines on Test at Rolls Royce. *Proceedings, International Society for Photogrammetry Commission 5 InterCongress Symposium*, Stockholm, Sweden, 14 p.

Torlegård, A. K. I., 1987. New Challenges of Close Range Photogrammetry. *Proceedings, Symposium on the Applications of Close Range Photogrammetry*, University of Melbourne, Australia, pp. 1–10.

Trinder, J. C., 1987. Processing of Digital Images for Photogrammetry. *Proceedings, Symposium on the Applications of Close Range Photogrammetry*, University of Melbourne, Australia, pp. 11–22.

Wong, K. W., and W. H. Ho, 1986. Close-Range Mapping with a Solid State Camera. *Photogrammetric Engineering and Remote Sensing*, 52(1):67–74.

(Received 9 March 1988; accepted 26 April 1988; revised 9 June 1988)