INDMET: AN INDUSTRIAL ORIENTED SOFTCOPY PHOTOGRAMMETRIC SYSTEM

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In many instances, photogrammetry may be considered advantageous over other deformation monitoring techniques as it is a non-contact method of remote measurement which also yields a visual record (i.e. the imagery) of the area being monitored. Softcopy photogrammetry offers many advantages over conventional hardcopy approaches since the imagery is available in a computer compatible form. In terms of data processing, the capabilities of fast data capture, automatic image point recognition and measurement and real-time or near real-time data reduction permits a flexible image measurement approach.

A close-range softcopy photogrammetric system for industrial machinery deformation monitoring has been developed by the Department of Geomatics Engineering at The University of Calgary. This paper presents an overview of the hardware and software development of this system. The mathematical models used for target measurement and photogrammetric estimation as well as system calibration and network design are detailed. Applications of this system are also presented. Finally, an overview of current system developments is given.

Dans un grand nombre de cas, la photogrammétrie peut être avantageuse comparativement à d'autres techniques de surveillance des déformations parce que c'est une méthode sans contact de mesurage à distance, qui produit également un enregistrement visuel (c.-à-d. l'imagerie) du secteur sous surveillance. La photogrammétrie à images numériques offre plusieurs avantages sur les approches conventionnelles à images imprimées puisque l'imagerie est disponible sous une forme compatible à l'ordinateur. En terme de traitement des données, les capacités de captage rapide des données, de reconnaissance et de mesurage automatiques rapides de points d'image, ainsi que la réduction de données en temps réel, ou presque, permettent l'adoption d'une approche flexible envers le mesurage à partir d'images.

Un système de photogrammétrie à images numériques à courte portée pour la surveillance des déformations de machinerie industrielle a été mis au point par le département de génie géomatique de l'université de Calgary. Cette étude présente un aperçu du développement de l'équipement et des logiciels de ce système. Les modèles mathématiques utilisés pour le mesurage des cibles et l'estimation photogrammétrique, ainsi que la calibration du système et la conception de réseaux sont exposés en détail. On présente également des applications du système. Pour finir, on présente un aperçu des développements actuels du système.

Introduction

Industries using high speed rotating machinery frequently require precise orientation information for the correct adjustment of the shafts. This is of particular importance when the mechanical train consists of several components such as a turbine, gear box and compressor. In such cases, the alignment of the shaft sequences to ensure collinear or parallel conditions is critical. When such conditions are not precisely met, component failure, such as coupler breakdown, can be expensive, especially in terms of lost production costs. Alignment strategies have routinely used methods which are well known to the millwrights in charge of these operations. These methods are generally one or two dimensional in nature which is not sufficient for many alignment procedures. Three dimensional information is often required to define the spatial orientation of the shafts with respect to one another as well as to other machinery or equipment in the vicinity.

To assist industry in finding solutions to such alignment problems, the Department of Geomatics Engineering at The University of Calgary has been actively involved in a cooperative research and development project entitled the Dynamic Alignment Project (formerly Industrial Alignment Project). Several new alignment techniques have already been developed under this project. In particular, total station methodologies using multiple

and single instruments have been successfully tested [*Teskey et al* 1994]. Because of the dynamic nature of these deformation problems, near-real time observation methods are needed. To this end, a digital camera based system (INDMET) was developed whereby multiple images of the same object (i.e. set of targets) could be simultaneously recorded using several cameras and subsequently processed to estimate point coordinates. The details of the associated hardware and software components of this system are outlined in the following sections.

System Hardware

The image acquisition component of the softcopy photogrammetric system consists of a pair of COHU 4810 charge-coupled device (CCD) monochrome frame transfer video cameras. Each camera has an active image area of 8.8 mm x 6.6 mm (754 x 488 sensor elements) and has been fitted with a 12.5 mm f/1.3 television lens. A calibrated fixed-base scale bar on which the cameras can be mounted has also been made available [*Obidowski* 1994].

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CCD video cameras are often erroneously termed digital cameras. Although the image acquisition process is digital in nature, the video output is in fact analogue. To recover the imagery, the output video signal, which contains both image and synchronization data, must be sampled using an external analog to digital (A/D) converter. The outlined system employs an Imaging Technology Inc. PCVISIONplus frame grabber fitted in a host 80486 66 MHz personal computer (PC). This card is capable of capturing 640 x 480 pixel images with 8 bit quantization per pixel.

Unfortunately, the A/D conversion introduces geometric systematic errors into the imagery. These distortions, caused chiefly by imperfect camera clock/frame-grabber synchronization, sampling interval differences and power supply fluctuations will be discussed in the "System Calibration" section of this paper. A truly digital camera performs the A/D conversion internally, thus eliminating the need for a frame grabber.

System Software

A software package entitled INDMET (INDustrial METrology), coded in the "C" programming language, has been developed to perform image acquisition and display, target location and image coordinate measurement. Individual targets are identified by the user and viewed under magnification for location purposes (see Figure 1). Using a program called BUNDLE, the measured control point and tie point images are simultaneously processed with the available object space information such as point coordinates. BUNDLE, as its name implies, is a self-calibrating bundle adjustment which has also been developed at The University of Calgary. This program can be spawned from within INDMET to solve photogrammetric problems in near real-time.

Targeting

Although the spatial resolution of most commercially available CCD sensors is much lower than that of photographic film, object space point accuracy approaching that of film-based systems may be realized using specialized targeting and controlled scene illumination. Planar targets consisting of black circular targets centered on squares of retro-reflective film have been found to be very effective for this system. The circular portion of the target has been modeled as a rotated ellipse as it appears under perspective projection in the imagery. Sub-pixel edge location observations along each pixel row or column about the circumference of the ellipse are achieved using the moment-preserving method of edge detection. Target center image coordinates are then estimated by fitting the edge observations to the a rotated ellipse model using the method least squares [*Cosandier and Chapman* 1992 and 1993]. Estimated target coordinate accuracies of 0.03 to 0.05 pixels are routinely obtained using this procedure.

A three-dimensional calibrated control field consisting of twenty-six of these targets has been constructed for the purpose of calibrating the softcopy photogrammetric system (see Figure 2).

System Calibration

Prior to any application of this system for precision close-range measurement, the cameras must be calibrated to determine the following internal geometric characteristics:

- Principal point position and focal length (basic elements of interior orientation).
- Radial lens distortion.
- Decentering distortion.

For analog video cameras, the term system calibration is more appropriate than strictly camera

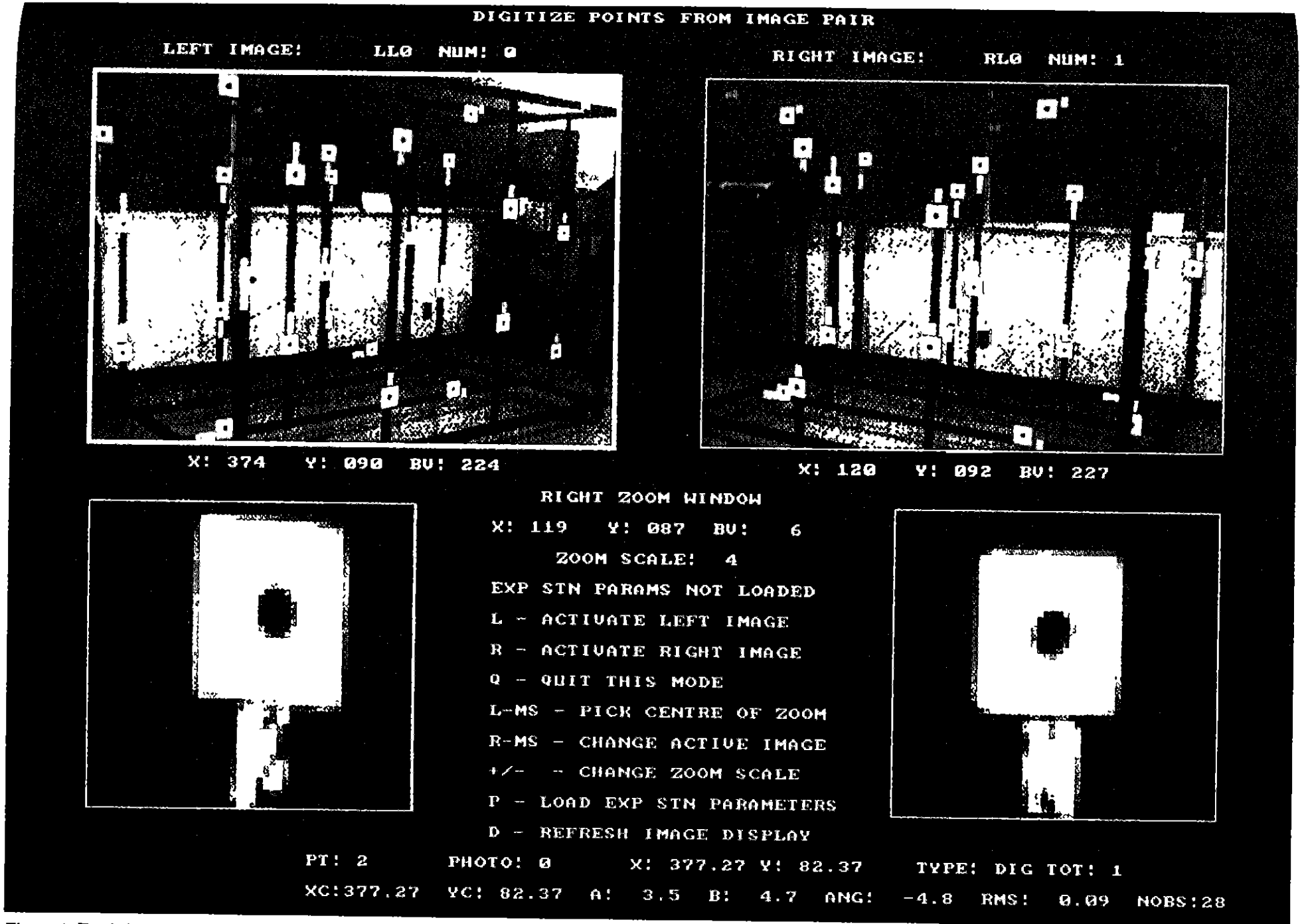

Figure 1: The INDMET System Being used for Target Location.

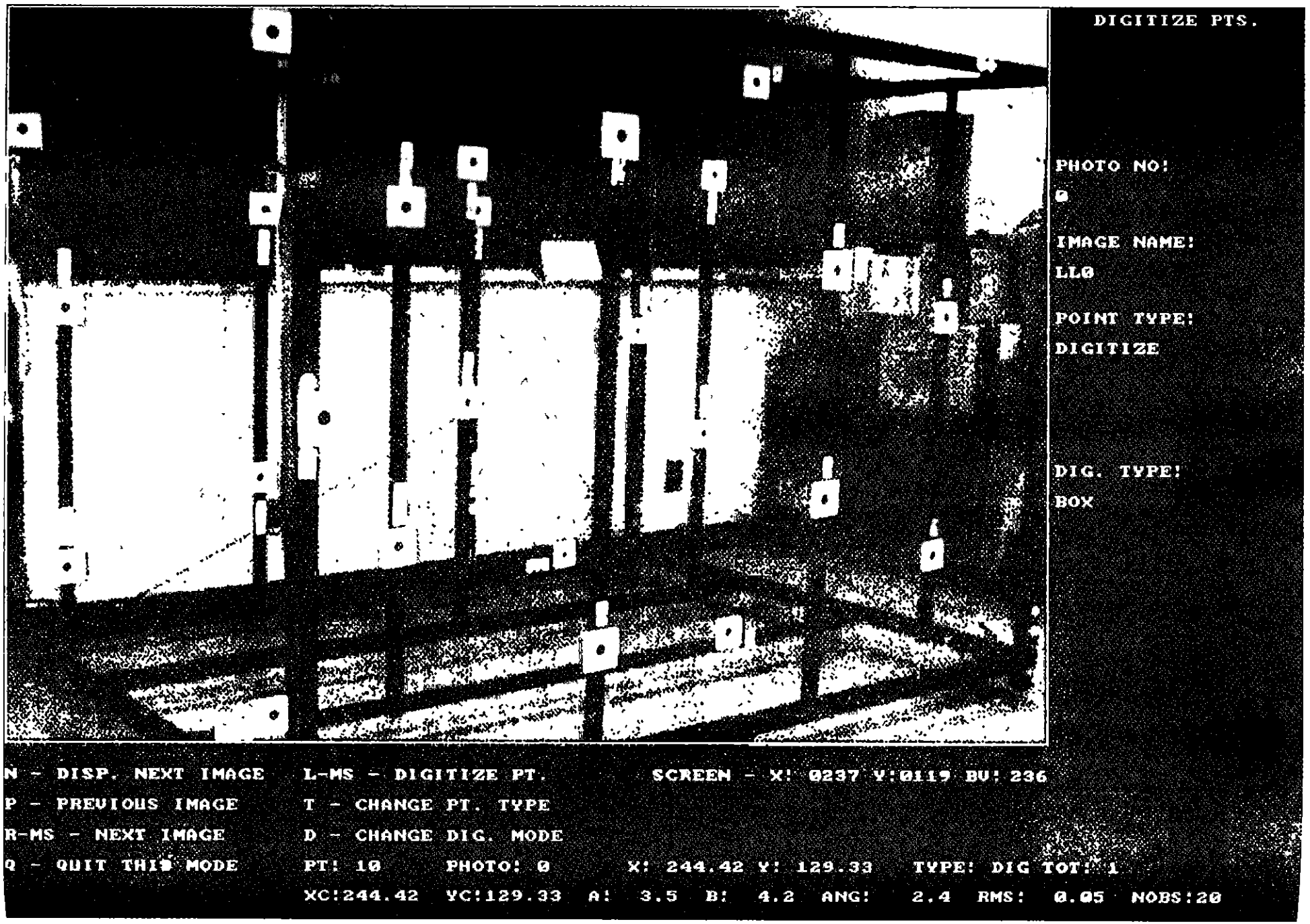

Figure 2: The Target Control Field as Viewed on the INDMET System.

calibration. This is because an additional interior orientation parameter, scale in the *x*-axis direction of image space due to non square pixels, is also estimated in the calibration procedure. This scale arises from the difference between the camera clock frequency, governing video signal output of the image data, and the frame grabber sampling frequency. Essentially, this creates rectangular pixels.

Because digital image coordinate systems are typically left-handed and photogrammetric object space is typically right-handed, an additional reflection factor (-1) must be incorporated into the *y* collinearity equation. In BUNDLE, a *y*-axis scale parameter has been added to account for both the *x*-axis scale and the reflection. Thus, the *y*-axis scale factor is simply the negative reciprocal of the actual *x*-axis factor. The collinearity equations with the additional parameters used are given by the expressions outlined in *Cosandier and Chapman* [1992] and *Obidowski and Chapman* [1993].

To estimate these parameters, a network of approximately twelve exposure stations about the control field is established. Convergent imagery is utilized to reduce the correlation between the perspective center coordinates and the interior orientation parameters. Secondary correlations between the omega and phi rotation angles, the principal point and the decentering distortion coefficients are suppressed by incorporating exposure stations with orthogonal kappa rotation angles into the network. Image noise is reduced by capturing a sequence of images at each exposure station and taking the arithmetic mean of the digital grey values of the sequence.

Following the measurement of the target image coordinates via the edge location and ellipse fit, the calibration parameters are estimated in the bundle adjustment. Analysis of the image coordinate residuals reveals a systematic effect in the x-axis direction (along pixel rows). This effect, called linejitter, is caused by errors in video signal/frame-grabber synchronization.

Practical Considerations

As in the calibration process, convergent imagery is employed for applications of this close-range system. The convergence angle between the optical axes of the cameras plays a fundamental role in the homogeneity of photogrammetric object point estimation. Although an angle of ninety degrees is desirable, there are limiting factors preventing the successful application of such ideal geometry. The first reason is that the retro-reflective property of the target film degrades substantially at angles of approximately forty-five degrees relative to the target surface normal. Second, a highly convergent imaging configuration affords less redundancy during the ellipse fit as the targets are highly elongated.

Since photogrammetric measurements in image space do not implicitly contain any object space datum information, as do many types of geodetic observations, all seven datum parameters must be explicitly defined. Three possible approaches to photogrammetric network datum definition include:

- Fully constrained solution: all object space control points are held fixed.
- Minimally constrained solution: only the minimum number of object space points (two plus one component, or a combination thereof) are held fixed.
- Free network or inner constraint solution: no control points are fixed; the network is constrained to its center of gravity with the Helmert transformation.

While the first scenario is commonly used in aerial photogrammetry, precise establishment of stable control points for close-range industrial applications can be cumbersome if not nearly impossible. Furthermore, an over constrained solution can potentially introduce undesirable geometric distortions in a network. A variation of the second approach using two cameras has been experimented with as an alternative.

Network translation and orientation elements may be defined by simply treating the perspective center coordinates and orientation angles respectively constant for one of the cameras. This can be done by either omitting the partial derivatives with respect to these parameters from the column space of the first design matrix or by assigning high *a priori* statistical weights. To complete the set of minimal constraints, network scale must be defined. With the cameras mounted on the ends of the fixed-base scale bar, an observation for the spatial distance between their perspective centers can be incorporated into the bundle adjustment to fulfill the datum requirements. The exterior orientation elements of the second camera can then be estimated given a sufficient number of tie points (a minimum of five) common to both images.

Experiments have been conducted in both laboratory and industrial environments to test this system. Induced object point spatial displacements on the order of 0.20 mm have been

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successfully recovered in both settings. This figure should improve with higher resolution cameras. However, problems with long term observations, i.e. over a period of several hours, drifting of image points have been encountered. This interior geometry instability may be remedied with completely digital cameras.

Current Research

During data processing, the current system requires the user to manually locate each target in each image with the PC's mouse.

During data processing, the current system requires the user to manually locate each target in each image with the PC's mouse. The operator must also manually enter an integer to identify each target. Research is presently being conducted into automating both of these processes.

The great contrast in reflectance between the target components is a property which can be exploited for target location. While image correlation could be used for the location task, it is very computationally expensive if external geometric information is not available to reduce the search problem from two dimensions to one. This is quite often the case in close-range photogrammetric monitoring applications, especially for the first measurement epoch (assuming stable exposure stations). A simpler image segmentation procedure based upon edge strength—that is, gradient filter response magnitude—may be used instead. Once approximately located, precise target position estimation can be performed with the ellipse fit.

One approach to target identification is to employ a set of symbols to represent integers which could be mounted on or near the targets. A means of recognizing those symbols which is invariant under the perspective projective transformation of the image formation process is thus required. However, if the ratio of the camera to object distance over the object relief is sufficiently large, as is the case for planar targets, a projective transformation may be approximated with a two-dimensional affine transformation. Properties of the symbols which are invariant under affine transformation may then be derived for the purpose of pattern recognition. Thus, symbols appearing in images may be classified using libraries of the properties for known symbols. One example of invariant quantities under affine transformation is moment invariants. These invariants are functions of the geometric moments of a planar object such as the proposed identification symbols.

An investigation is also being conducted into the use of a digital camera for this system. A truly digital camera has the advantage over its analog counterpart in that there is no linejitter. Furthermore, there should not be an x-axis scale factor due to sampling frequency differences as A/D conversion is done within the camera itself. However, there still may be a scale present if the sensor element spacing in the x- and y-axis directions are not equivalent. To this end, a Kodak DCS 420 Colour digital camera has been purchased and is currently undergoing preliminary testing.

Conclusion

The history and the future in softcopy photogrammetry research at The University of Calgary has been presented. The described close-range system has been shown to be effective in both laboratory and industrial environments. Future use of digital cameras with higher resolution sensors will not only improve the system in terms of measurement precision but also eliminate systematic errors due to imperfect synchronization. Finally, automation of the target location and identification processes should produce a complete system for close range softcopy photogrammetry.

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