# PERFORMANCE EVALUATION OF SEQUENTIAL ESTIMATION IN VISION METROLOGY

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## ABSTRACT

Parameter estimation in photogrammetry is generally accomplished by means of a *simultaneous* least-squares adjustment in which *all* observational data must be at hand prior to solution. It follows that, despite the rapid turnaround provided by digital imagery and current measurement technology, the simultaneous adjustment cannot offer an indication of quality until acquisition and measurement are complete. On-line quality control of single-sensor vision metrology (VM) can be implemented effectively through on-line triangulation (OLT) with *sequential* estimation. Here, object point precision is monitored directly within the data acquisition phase. One may then be continuously aware of the quality of the photogrammetric network as it takes shape. In addition to enhancing the efficiency of the triangulation procedure, the risks of collecting either insufficient or surplus imagery are diminished. Furthermore, any localised weaknesses within the overall network can be isolated and corrected. Sequential estimation, in combination with established network design principles, can significantly influence economy and productivity in the industrial environment. This paper provides an overview of sequential estimation for single-sensor VM. The general sequential problem is discussed, emphasising significant implementational aspects. Evaluations of practical testing are presented. Additional potential applications of sequential estimation in VM are briefly outlined, including its use in real-time, multi-sensor systems. Promising experimental results clearly demonstrate that OLT can be an effective and valuable tool in industrial VM.

## 1. INTRODUCTION

Digital close-range photogrammetric systems for industrial metrology have evolved dramatically in recent years with a corresponding increase in productivity, robustness, and reliability. This is due in large part to advanced computer technology and the relatively recent availability of large format CCD (charge-coupled device) cameras. An on-line single-sensor system, though not capable of a truly real-time response, can nevertheless furnish results in a fast and efficient manner. Furthermore, the single-sensor system has been shown to satisfy many of the diverse accuracy requirements and specifications found in industry (Fraser and Shortis, 1995; Maas and Kersten, 1994). The inherent potential for automation afforded by digital imagery is blurring the once distinct tasks of image acquisition, measurement, adjustment, and analysis. Fully automated image measurement, orientation, and triangulation is now accomplished without operator intervention utilising a combination of hardware and software innovations.

Fraser (1997) details a number of these innovations. The use of retro-reflective targets in conjunction with image processing algorithms affords virtually instantaneous image measurement. Exterior orientation (EO) devices and coded targets enable automatic image orientation without prior knowledge of the object point field. With the development of the so-called smart camera, image measurement and orientation can take place within the sensor via an onboard computer. An example is the INCA 4.2 (from **IN**telligent **CA**mera) camera developed by Geodetic Services, Inc. (Geodetic Services, Inc., 1996).

If a *closed form* resection is used for image EO, the user need not provide approximate parameter values (Zeng and Wang, 1992). The determination of point correspondences between images, a major obstacle to full automation, is typically accomplished by means of epipolar geometry (Gruen, 1985b; Dold and Maas, 1994).

In close-range industrial photogrammetry the determination of three-dimensional object point coordinates is of primary concern. These coordinates are usually obtained through a *simultaneous* least-squares estimation process commonly called the bundle adjustment (Brown, 1958). The word simultaneous implies that all image coordinate observations must be available before the adjustment. It follows that, despite the high productivity afforded by digital imagery and current measurement technology, the quality of the results cannot be properly assessed until all image acquisition and measurement are complete.

After an optimal convergent camera station network is in place, the use of multiple exposures is the principal means of improving object space precision. On-line quality control of the photogrammetric process can be implemented effectively through on-line triangulation (OLT) with *sequential* estimation. Object point precision can be monitored directly during data acquisition. The quality of the photogrammetric network can then be monitored as it develops. In addition to enhancing the efficiency of the triangulation procedure, the risks of collecting either insufficient or surplus imagery are reduced. Weaknesses within the network can be isolated and corrected. The photogrammetrist, while still on site, can interactively strengthen the network geometry until a desired level of accuracy is obtained. Sequential estimation, in combination with established network design principles, can have a significant positive influence on economy and productivity in the industrial environment. Although sequential estimation has been utilised for aerial triangulation, its suggested application for industrial quality control of the photogrammetric process (Kersten *et al.*, 1992) has for the most part remained unexamined.

This paper explores the utilisation of sequential estimation for OLT in single-sensor VM as reported in Edmundson (1997). Sequential estimation is discussed generally and in direct relation to VM. Significant implementational aspects are emphasised including system response time, sequential estimation in non-linear systems, datum establishment, and the compensation of systematic errors. Finally, results of practical testing are described.

## 2. SEQUENTIAL ESTIMATION

### 2.1 General Background

For a variety of estimation problems, it is useful to repeatedly obtain solutions for a data set to which observations are being sequentially added or removed. A frequently cited example is the determination of a satellite's orbit. One approach to this problem is to perform a simultaneous adjustment every time the data set changes. However, fast response is generally critical for problems of this nature and the efficiency of performing multiple simultaneous adjustments is often unacceptable. For such dynamic applications, sequential estimation is computationally more efficient than simultaneous, in that observations may be added to an existing system as needed. However, it may not always be as rigorous. Observations that prove to be erroneous may be either removed from the system or replaced. In engineering, sequential estimation is often called filtering or process identification. In geodesy and photogrammetry the terms adjustment in steps or phased adjustment are also used.

Sequential estimation is utilised in signal processing for communications and control, satellite navigation, spacecraft orbit determination, and missile tracking. In image processing and analysis, sequential methods have been used for image resampling, aspects of orthophoto production (Baltsavias *et al.*, 1991), and for the dynamic tracking of objects in image space (Deriche and Faugeras, 1990). Filtering procedures are also used in both static and kinematic Global Positioning System (GPS) processing (Leick, 1995).

The photogrammetric process is inherently sequential. Images are both acquired and observed in a sequential manner. In the on-line environment, this characteristic can be successfully exploited through the use of sequential estimation. In aerial photogrammetry, OLT has traditionally served as a near real-time means of quality control of the measurement process through the detection and identification of gross errors. Quality control of the single-sensor VM process follows naturally from the original vision of OLT. Image acquisition and measurement can occur virtually simultaneously when utilising an on-line digital camera. When new observations become available, the existing system can be updated without starting "from scratch" with the entire new data set. A comprehensive historical background of sequential estimation as applied to OLT can be found in Gruen (1985a). Several recent studies have examined its use in non-topographic applications. These include robot vision (Gruen and Kersten, 1992), autonomous vehicle navigation (Edmundson and Novak, 1992), and image sequence analysis (Kersten and Baltsavias, 1994).

### 2.2 Sequential Algorithms

Notable sequential algorithms which have been examined for OLT include the Kalman filter, which updates the inverse of the normal equations matrix (Mikhail and Helmering, 1973), the "Triangular Factor Update" (Gruen, 1982) which updates the factorised normal equations directly, and Givens Transformations (Blais, 1983).

Givens Transformations offer a number of advantages over other such algorithms with respect to both general least-squares and sequential estimation (George and Heath, 1980; Runge, 1987; Holm, 1989). An orthogonal transformation technique based on the use of plane rotations to annihilate matrix elements, this approach provides a direct method for solving linear least-squares problems without forming the normal equations. Only one row of the design matrix is processed at a time, making it ideal for sequentially adding or deleting observations in an on-line environment.

The application of Givens Transformations to the design matrix yields a matrix equivalent to that obtained by applying the Cholesky factorisation to the normal equations matrix. It follows that a normal equations matrix factorised with Cholesky can be directly updated with new observations via Givens Transformations. A modified form of Givens Transformations was chosen for this study. Computationally less expensive than the original formulation, it avoids the calculation of square roots, requires fewer multiplications, and facilitates weighted least-squares estimation (Gentleman, 1973). In the following, this method is referred to as GWSR (Givens Without Square Roots). As the original Givens method is compatible with Cholesky, GWSR is compatible with the so-called $U^TDU$ decomposition.

For a mathematical description of general sequential estimation the reader is referred to Gruen (1985a). A detailed derivation of Givens Transformations may be found in Edmundson and Novak (1992), Kersten *et al.* (1992), or Edmundson (1997).

## 3. IMPLEMENTATION ISSUES

Here, implementation issues in OLT with respect to close-range, convergent photogrammetry are discussed. These include response time, sequential estimation in non-linear systems, and datum establishment.

### 3.1 System Response Time

Response time is critical in on-line VM applications and particularly so in the industrial environment where inspection costs are directly influenced by the extent of site disruption. The efficiency of the sequential procedure is significantly influenced by the size of the normal equations system, which in turn is dependent upon the number of system parameters and the method of parameter elimination utilised.

Ignoring camera self-calibration, phototriangulation involves six exterior orientation parameters for each image and three coordinate parameters for each object point. Consider a system involving *m* images and *n* object points. In the standard formulation of the bundle adjustment, object point parameters are eliminated, leaving a *6m x 6m* system of orientation parameters. If there are significantly fewer point than image parameters (*3n << 6m*), eliminating the image parameters provides a more efficient solution. This alternative approach, which is often termed reverse parameter elimination, is also useful in the simultaneous adjustment. Moreover, the incorporation of point-to-point distance constraints and inner constraints for free network adjustment is simplified using this method.

Efficiency is also improved through the exploitation of the sparsity patterns of the reduced normal equation system. A special matrix storage technique described in Gruen (1982) is modified here to accommodate the elimination of image sensor parameters as discussed above. This technique, combined with GWSR, facilitates the direct update of the *reduced* normal equations. An example is shown in Figure 1.

The light shaded portion of the figure represents the reduced normal equations for six object points. Assuming a consistent system at any particular stage, this portion of the matrix is fully populated. This structure is expanded by six rows and columns (dark shaded area) to provide storage for the submatrices associated with a particular image. The introduction of a new image into the system begins by setting all matrix elements of the image submatrices to zero. All observation coefficient vectors for a given image are rotated through the entire structure via GWSR. All subsequent images are treated in the same manner. If observation deletions or re-measurements are required in a previously introduced image, its existing associated submatrices must be re-positioned in the dark shaded areas. The necessary observation vectors are then rotated through the system with weighting appropriate for either insertion or deletion. Back substitution yields the current solution vector for the object point parameters.

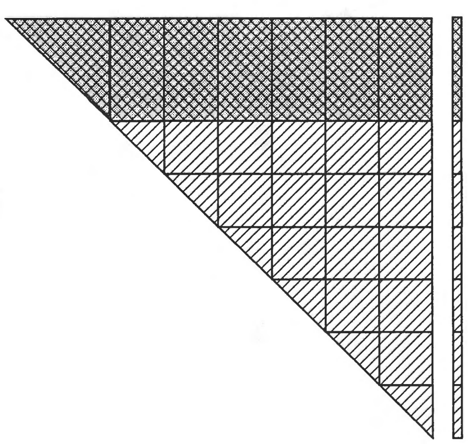

Figure 1: Reduced normal equation matrix structure for sequential estimation.

### 3.2 Sequential Estimation in Non-Linear Systems

The problem of sequential processing in a non-linear model such as the collinearity equations is addressed in Mikhail and Helmering (1973). Of concern is the issue of updating parameter values during OLT. The primary advantage of sequential estimation lies in the ability to update the system rather than completely rebuild it with the augmented data set. In a linear system this poses no problems. With a non-linear model, parameter values cannot be updated sequentially unless the entire observation equation system is re-linearised. Coarse initial values will likely cause the solution vector to drift as data is added. This in turn will hinder the efficient computation of precision.

Sufficiently accurate initial values are therefore a prerequisite to preventing drift. In close-range VM, it is assumed that measurement is restricted to signalised targets in highly convergent imagery. If all targets appear in all images, providing initial values of sufficient quality for sequential estimation is straightforward. A minimum of four convergent images is required for a consistent, reliable system. This basic configuration should be of optimal geometric strength in order to maximise triangulation accuracy.

Once this minimal system has been adjusted, parameters for object point, exterior orientation, and camera parameters are available to proceed sequentially. New images can now be incorporated into the system. Initial exterior orientation parameters for new images are obtained via space resection. The parameters from the initial adjustment should be sufficient to avert significant drift in the updating process. If drift does occur, a logical remedy is to perform a simultaneous solution. This provides a "clean" version of the parameter vector that may be used as the basis for continued updating. It is unlikely to cause any significant delay as it can be performed quickly while the photographer is moving to another location or is capturing another image.

If the initial network cannot include all targets, new object points will appear during the sequential phase as their observations arise. Although an object point's coordinates are uniquely determined with three observations, coordinate precision and the reliability of observations are strongly tied to the number and configuration of associated rays. If a statistical blunder detection process such as the well-known data snooping is utilised, four well-distributed rays per object point are necessary for both detection and location. Therefore, a point should not be introduced until this requirement is fulfilled. At that stage, initial point coordinates are determined by least-squares intersection and all observations for the point can be sequentially incorporated into the system.

### 3.3 Compensation for Systematic Errors

For a full bundle adjustment with camera self-calibration, the additional parameter model typically includes interior orientation parameters of focal length and principal point coordinates, plus those of radial and decentering distortion, differential scaling, and image axis non-orthogonality. The capability of recovering these parameters is enhanced in a convergent network, and their presence has a direct influence on object point precision. As the primary objective here is the monitoring of object point accuracy via sequential estimation, these parameters should be included, and it is a simple matter to do so.

### 3.4 Datum Establishment

It is necessary to establish an optimal, consistent network geometry prior to the start of the sequential procedure. Countering the datum defect throughout the sequential procedure is an important consideration. Minimal constraints can be imposed by fixing (or weighting) seven coordinates from three well-distributed object points. In industrial photogrammetry, minimal constraints are typically imposed by means of a free network adjustment using inner constraints (Fraser, 1982). This is done by bordering the singular normal equations matrix with a transformation matrix *G* which can have various forms, one of which fulfills the condition that $AG = 0$ (Blaha, 1971).

## 4. A PRACTICAL EXAMPLE

Here, a simple, practical example is provided to illustrate OLT for monitoring object point precision in a typical single-sensor, close-range VM application. This example demonstrates the efficiency of the sequential procedure as compared to the simultaneous solution and allows a direct comparison to be made between the resulting object point standard errors from both methods.

An INCA 4.2 digital camera with a SunPak DX 12R ring strobe was used for the test. This camera has a 17mm lens fixed at infinity focus. The sensor is 2K x 2K with a pixel size of 9 micrometres square.

Figure 2 shows an INCA image of the target array used for this test. The testfield consists of 61 retro-reflective targets. A 2 metre scale bar was introduced. Field dimensions are 3.0 metres in both width and height. No fixed control points were utilised as the datum was established via a free network adjustment. Initial values for object point coordinates were available from a previous survey.

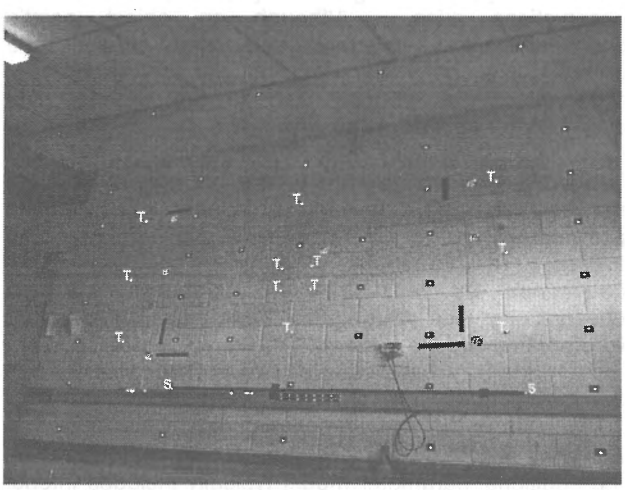

Figure 2: INCA 4.2 testfield image. Retro-reflective targets are highlighted. Tooling targets are marked with "T" and scalebar targets with "S".

Figure 3 shows a perspective view of the testfield and camera station configuration. Four images were acquired at each of six stations with roll angles of 0, 90, 180, and 270 degrees. The average camera-object distance is approximately 4 metres, resulting in an image scale of about 1:240. All targets appear in all images and the field fills the image format as much as possible.

All images were taken in off-line mode, stored on a removable PCMCIA disk, and then transferred for measurement and reduction to a Pentium 120 personal computer with 32 megabytes of RAM. The retro-reflective targets were measured using an intensity weighted centroiding algorithm. All image measurement and simultaneous and sequential adjustments were performed in the *Australis* digital photogrammetric processing system. This program, developed in the Department of Geomatics at The University of Melbourne served as the platform for the development of close-range OLT.

### 4.1 Simultaneous Adjustment

A simultaneous, self-calibrating free network adjustment was performed with all 24 images. The additional parameter model used was as described in Section 3.3. The resulting r.m.s. of image coordinate residuals was 0.14 μm. The r.m.s. of object space standard errors in the X and Z coordinates was 8.7 μm. That for the Y coordinate was 18.0 μm. This results in an overall point error of 22 μm and relative accuracy of about 1:190,000.

### 4.2 Sequential Processing

As mentioned, once a basic, optimal network geometry is in place, the use of multiple exposures at roughly the same image stations is an effective means of enhancing object point precision. This basic network must be in

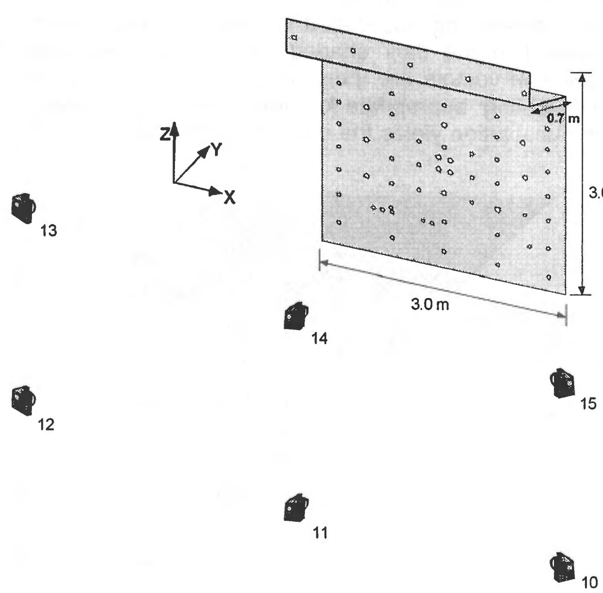


Figure 3: Calibration testfield and network geometry. Four images were acquired at each station with rotation angles of 0, 90, 180, and 270 degrees.

place prior to OLT, which then involves the re-acquisition of the network sequentially until a desired object precision is obtained. To simulate this, the 24 testfield images were divided into four sets of six. Each set consisted of one image from each station and included a variety of roll angles to afford successful self-calibration.

An initial network was established with one of the four sets of six images. A simultaneous, free network adjustment was performed utilising the reverse parameter elimination procedure and the $U^TDU$ factorisation. With the resulting normal equation system as a foundation, the remaining images were then measured and added sequentially, using GWSR. Again, the previously described camera model was utilised throughout the procedure.

Prior to adding an image to the system sequentially, it is resected using all targets to optimise the initial exterior orientation values. Observations from a single image are incorporated into the system as a group. After adding each image, updated statistical measures are determined. The CPU time necessary for a single image update includes

1) bookkeeping for the new observations
2) the sequential addition of all observations to the system
3) inversion of the upper triangular, factorised normal equations
4) updating statistics including the redundancy and standard error of unit weight ($\hat{\sigma}_0$)
5) computation of the diagonal elements of the covariance matrix
6) calculation of the updated r.m.s of the object coordinate standard errors

### 4.3 Comparing Simultaneous and Sequential Methods

The simultaneous and sequential procedures were compared in terms of CPU time required for system updates. This comparison is shown in Figure 4. Changes in the r.m.s. of object coordinate standard errors were monitored as images were added in both procedures. A series of 19 simultaneous adjustments were performed, emulating the sequential procedure. The first adjustment included six images to establish the initial system. Each adjustment thereafter incorporated one additional image. The simultaneous adjustments utilised the standard fold-in procedure. CPU time recorded in the simultaneous procedure encompassed the entire adjustment. This included the iterative solution, a final full inversion of the normal equations matrix, and determination of the object coordinate standard errors.

In Figure 4, the abscissa represents the number of images in the existing system while the ordinate is the time required to add one image. A single image update consists of 61 image coordinates or 122 observations. Black bars depict times for adding one image sequentially. White bars represent the time required to perform a simultaneous adjustment with one additional image. For example, adding one image sequentially to a six image system required approximately 1.6 seconds while the simultaneous solution for the full, seven-image system required 1.1 seconds.

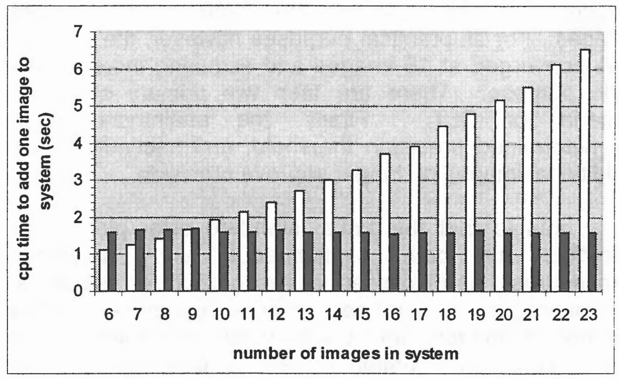


Figure 4: Comparison of CPU times between simultaneous and sequential methods for adding one image to an existing 61-point system.

As seen in the figure, the time for a sequential single image update remains relatively constant regardless of the size of the system. The average time for a single image update is 1.611 seconds. This equates to an average update time of 0.013 seconds per observation. Minute deviations from this average are likely due to unrelated CPU processes. For updates to systems with up to eight images, the simultaneous adjustment is slightly faster. Both procedures show similar efficiency for a nine-image system. As the number of images grows beyond nine, the sequential approach becomes increasingly more efficient.

### 4.4 Monitoring Object Point Precision

A plot of the changes in the r.m.s. values of object point standard errors as images are added to the system is displayed in Figure 5. As the values obtained in the simultaneous and sequential procedures were identical, the figure represents both. The abscissa and ordinate represent the number of system images and the r.m.s. values of object coordinate standard errors, respectively.

It is clear from the figure that beyond approximately 18 images the r.m.s. values of all coordinate standard errors are approaching a practical minimum. With three images at each camera station, 18 images account for three full collections of the initial network. From 18 to 24 images there is an improvement of only about 1 μm in object

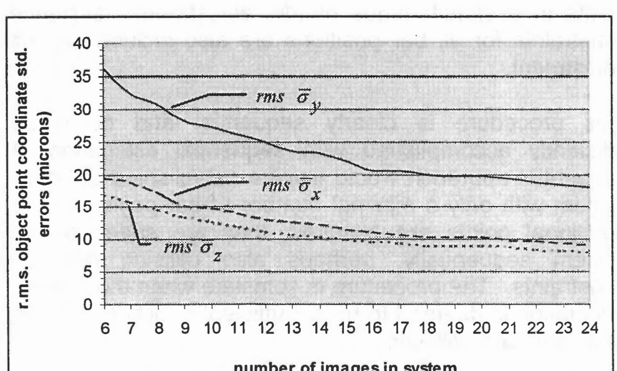


Figure 5: Tracking r.m.s. values of object coordinate standard errors with simultaneous and sequential methods.

space. For demonstration, the graph is plotted to 24 images. For all practical purposes however, the solution has converged at 18 images and acquiring more serves little purpose. There are then two primary cessation criteria for OLT. Firstly, the attainment of a predetermined precision threshold, and secondly, when additional images no longer improve precision.

It is notable that the r.m.s. standard error plots were identical for both simultaneous and sequential procedures. As discussed in Section 3.2, for sequential estimation in a non-linear model, parameter values cannot be updated unless a complete re-linearisation of the observation equation system is performed. In the presence of coarse initial values we would anticipate some parameter vector drift and some degree of discrepancy between the simultaneous and sequential solutions. In this exercise, however, all targets were visible in all images and excellent parameter values were available from the initial six-image adjustment upon which the OLT process was based. In any event, OLT is envisioned as a means to indicate overall object precision. Whether or not parameter drift is encountered, a rigorous simultaneous adjustment should be performed after all data is available.

## 5. ADDITIONAL CLOSE-RANGE APPLICATIONS

Sequential estimation has potential in other areas of VM. It has been previously utilised for interactive geodetic network design (Mepham and Krakiwsky, 1984). The algorithms and procedures outlined here could be implemented for photogrammetric network design with little modification. Other possibilities include off-line batch processing and the verification of image point correspondences.

Another likely application is the orientation of real-time VM systems consisting of two or more synchronised CCD cameras in a multi-sensor network configuration. Often, only a minimal amount of control will be utilised to provide an initial exterior orientation. A procedure to strengthen the orientation is described in Haggrén and Heikkilä (1989). A scale bar, possibly incorporating multiple scale lengths through the placement of retro-reflective targets, is moved throughout the measurement volume. At each bar position, image points are recorded by all sensors. After a number of bar positions have been recorded, the exterior orientation is redetermined using all recorded points in a simultaneous bundle adjustment. Distance constraints for all bar positions are also included in the adjustment.

This procedure is clearly sequential and could be efficiently accomplished with sequential estimation. A sequential approach would involve establishing an initial system with only a minimal number of bar positions. As additional points are acquired, they are added to the system sequentially, perhaps also utilising distance constraints. The procedure is complete when the exterior orientation is deemed to be of sufficient quality to support real-time data collection.

In a preliminary feasibility study of such an approach, a simulation was perfomed with a two-camera system and a scale device with four retro-reflective targets and two known distances. An initial system was captured consisting of four bar positions plus six additional points. Twenty-five additional bar positions were then recorded. With the camera model parameters fixed, a free network bundle adjustment was performed to obtain the exterior orientation of both cameras. To simulate the sequential procedure, each additional bar position was added to the system individually and a single bundle adjustment iteration performed. Sigma values for the six orientation parameters were recorded for each additional bar position. The r.m.s. of the camera station coordinate sigmas and orientation angle sigmas are shown plotted against the number of bar positions in Figure 6.

It was anticipated that the resulting standard error curves would have been obviously asymptotic in nature, approaching a finite value beyond which one could assume that the exterior orientation would not improve with additional bar positions. What is clear from the graphs however, is that there is no clear point at which it can be judged that the system has stabilised. Although not initially encouraging in terms of using sequential estimation for this task, the results could be due to the use of the free network adjustment with the collinearity equations. Here, the precision of the camera exterior orientation is directly tied to the datum, which is changing with every new bar position. Performing a sequential relative orientation utilising the coplanarity model may provide more desirable results since a clearer picture of the relative precision of the exterior orientation of the real-time VM set-up would be obtained. A further issue still to be resolved in this regard at the time of writing is the impact upon precision of the scale constraint imposed

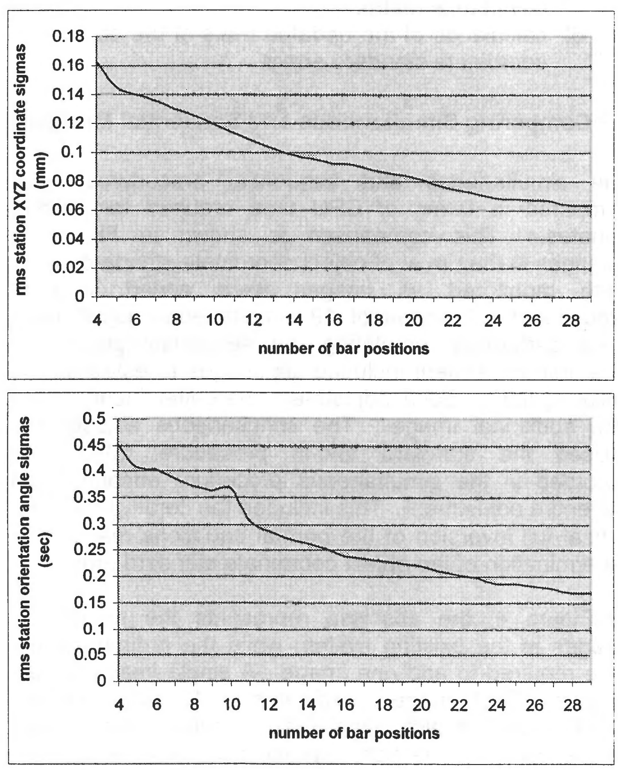


Figure 6: Orientation of real-time VM system using sequential estimation. Plots show the r.m.s. of station coordinate sigmas (above) and station orientation angle sigmas (below) vs. the number of bar positions.

with each bar position. Whether the inclusion of a rigorous constraint imposed at each sequential update has a more positive impact than simply averaging the overall scale information following the exterior orientation phase has yet to be determined.

## 6. CONCLUDING REMARKS

This paper has focused primarily on the application of sequential estimation techniques in OLT to single-sensor VM systems. The potential for these systems is largely dependent upon the refinement of techniques such as sequential estimation, which emphasise increased levels of automation in data acquisition and analysis. Important issues in OLT relative to single-sensor VM have been discussed including system response time, approximate values, additional parameters, and datum issues. As outlined in Section 5, there are a variety of applications in close-range VM, which could potentially benefit from a sequential approach, including the orientation of real-time multi-sensor CCD systems.

The overall advantage of the sequential solution as developed here stems from a variety of factors. Most importantly, the observation equation system is never re-linearised throughout OLT. Secondly, in the reverse parameter elimination method, the size of the normal equations is dependent upon the number of object points in the network. GWSR offers efficiency in terms of reduced mathematical operations. Moreover, the matrix structure of the $U^TDU$ factorisation provides an efficient approach to the computation of the cofactor matrix of the parameters. The test described in Section 4 provides an excellent demonstration of the power that sequential estimation through OLT brings to single-sensor VM. Monitoring object precision on-line can be performed effectively and with minimal cost within the measurement procedure. It follows that if the camera is physically connected to a computer, then measurement and OLT meld directly with the image acquisition phase.

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