14TH CONGRESS OF THE INTERNATIONAL SOCIETY FOR PHOTOGRAMMETRY
HAMBURG 1980

Commission V
Working Group V-1: Analytics of Close-Range Photogrammetry
Invited Paper

FROM ON-LINE TO REAL-TIME SOLUTIONS IN CLOSE-RANGE PHOTOGRAMMETRY

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ABSTRACT

Analytical on-line systems are shown to be well suited to close-range photogrammetry, because its typical variety of conditions and objectives is best handled by versatile interactive procedures. Their potential is analyzed and examples presented. Some on-line systems already contain elements of real-time processing. It is demonstrated how, by their expansion, photogrammetry may naturally evolve into real-time solutions in which measurement and evaluation phases overlap, if feedback information is available with a practically negligible delay. The resulting potential to monitor or control dynamic situations in biomedicine and engineering is demonstrated by practical examples.

INTRODUCTION

On-line photogrammetric methods are characterized by a direct use of computers which introduce elements of data processing already in the phase of data acquisition, in order to enable an early interpretation of results. The basic structure of an on-line procedure is represented by a straight sequence or a versatile combination of individual operational blocks, such as: 'measure - process - check - edit - modify'. Real-time elements may be involved in on-line processing, but usually only at the level of supporting functions. In general, an on-line approach is characterized by an efficient *operator-system interaction.*

Real-time processing is always time-contrained. It is applied to the monitoring, control or simulation of dynamic operations, with a recursive type of formulation working in a closed loop. Feedback information is utilized in each individual cycle. Ultimately, every real-time approach represents *an effort to automate a process.*

ON-LINE SOLUTIONS

Analytical reconstructions in close-range photogrammetry are characterized by features which, in general, clearly distinguish them from procedures used in cartographic applications. The high efficiency of aerial photogrammetry is achieved by securing uniform conditions and by adhering to standard solutions, whereas close-range projects deal with a broad scope of individual approaches. However, at least a certain degree of uniformity must be established in the development of software for on-line solutions. This is achieved by a suitable formulation of system functions and by interactive programs which can be readily modified by operators at the time of execution.

Generalized Formulation

The role of on-line systems in close-range photogrammetry was analyzed by Kratky (1976) and the following is a brief review of the most important facts which have a direct bearing on the formulation of on-line solutions:

- available cameras or special imaging systems very often do not comply with the established concepts of a metric camera;
- the geometry of non-conventional imageries must be established by independent calibrations and fitted to suitably modified projection equations in a standard formulation of collinearity or affinity conditions;
- the calibration of standard geometry can be optionally derived 'on-the-job';
- the separation of relative and absolute orientations is not suitable, and they should be replaced by a one-step universal procedure yielding elements of exterior and optionally of interior orientation;
- auxiliary data should strengthen exterior orientation by weighted constraints added to the solution;
- interactive editing of measured data, based on checking parallaxes and coordinate discrepancies, should be part of the solution.

One can assume that the available on-line system is capable of reproducing the required image geometry and of using it in the real-time control of image positioning, as needed for the detailed compilation of the model. The reconstruction of the model is then represented by the numerical solution, in which one derives orientation parameters by matching the images with the spatial model supported by object control information.

In off-line computations the photogrammetric model can be reconstructed from corresponding sets of corrected photo coordinates x', x'' matched with control coordinates X using an appropriate model for the geometry

$$\Delta X = X - X_o = \mu P x' \quad , \tag{1}$$

where projection matrix P (3,2) represents the orientation of the projection bundle or of the parallel beam (Kratky, 1976), μ is a scale factor, which is variable in central projections and constant in parallel projections, and $\Delta X = (\Delta X, \Delta Y, \Delta Z)^T$ are reduced object coordinates.

In on-line analytical systems the communication between photo and object coordinates is mediated by auxiliary model coordinates $x = (x,y,z)^T$ as expressed in a symbol form by

$$\begin{tikzcd} (x',x'') \arrow[rr, leftrightarrow, bend left, "g"] \arrow[r, leftrightarrow, "g_1"'] & x \arrow[r, leftrightarrow, "g_2"'] \arrow[d] & X \\ & \tilde{x} & \end{tikzcd} \tag{2}$$

The coordinate system of the model becomes a master for the other systems, including graphical output $\tilde{x}$. Before the on-line system takes advantage of the computer control ($x \rightarrow x', x''$) a minimum number of photo coordinates must be measured and parameters g computed. At this point the computer starts controlling the optical stereomodel which becomes parallax-free. With every new observation added, the orientation parameters are automatically updated in a new solution until the measurements are satisfactorily completed and edited by rejections and remeasurements, if necessary.

The computation proper is based on a rather arbitrary partitioning of vector g into g_1 and g_2. It is advantageous to assume equal photo and model scales and introduce an auxiliary coordinate shift C. Thus, the working equations of an on-line analytical system, which is physically controlled through the model, can be given by

$$x' = \lambda P^T \Delta x \quad , \quad X = C + mx \quad , \quad \tilde{X} = vX \quad , \tag{3}$$

where λ is a modified scale factor always close to unity, P is an appropriate rotation matrix and v is an arbitrary ratio to generate a graphical plot. The first formula in Equations (3) represents transformations for both images. The exterior orientation is fully returned to the $(x \rightarrow x')$ link except for the scale factor m which is used in the $(x \rightarrow X)$ computation. The measuring mark is operated in the directions of the object coordinate system. Other possibilities of arranging the return of information are discussed by Kratky (1976).

In a single model the individual points are intersected from pairs of conjugate rays. A collinearity or affinity condition can be applied to each ray, in a general form $F(g, l) = 0$. Here, vector l represents ideal photo coordinates. The real observations x', x'' are not consistent with the function F and yield residuals u. Vector g is formed by camera-related parameters g_o representing interior and exterior orientation of both pictures, and by object-related parameters g_x denoting unknown coordinates for all points which are not control-supported. A suitable elimination of g_x in the least squares formulation leads to modified normal equations

$$B_o^T P_o B_o g_o + B_o^T P_o u = 0 \quad , \tag{4}$$

where B_o is a (4n×18)-matrix of coefficients related to vector g_o and P_o is a weight matrix representing correlations introduced by the elimination of g_x. The normal equations are formed sequentially from individual point contributions with the use of (4×4)-matrices

$${}^jP_o = p_j(I - B_x(B_x^T B_x)^{-1} B_x^T)_j = p_j(I - B_x B_x^+)_j \quad . \tag{5}$$

Here, ${}^jB_x$ is a (4×3)-matrix associated with the coordinates of an object point P_j, ${}^jB_x^+$ is its pseudo-inverse and p_j is a weight derived from the coordinate difference ΔZ_j according to $p_j = 1/\Delta Z_j^2$. Ultimately, parameters g_o are computed from the accumulated normal equations

$$g_o = -(B_o^T P_o B_o)^{-1} B_o^T P_o u \quad . \tag{6}$$

The computation is completed by calculation of coordinates of individual intersected points P_j from updated residuals u_j

$${}^jg_x = -{}^jB_x^+ u_j \quad . \tag{7}$$

In this arrangement it is easy to build the normal equation system with the use of the same formulation for both control and intersection points. For a control point supported by all three coordinates it holds true that

$${}^jB_x = 0 \quad , \quad {}^jP_o = {}^jP \quad , \quad {}^jg_x = 0 \quad .$$

Auxiliary Constraints

The simplest way of utilizing constraints in a single model solution is to enforce some known or statistically expected value or relation among orientation parameters. This type of formulation increases the stability of the solution and prevents a major disagreement between the derived mathematical model and expected stochastic model. This particularly important, for instance, if only parts of stereoimages can be used for the reconstruction of the model and the equation system tends to be ill-conditioned. A constraint $F(g_o, c) = 0$ among parameters g_o is linearized to $B_c g_o - c = 0$ and enforced by an independent contribution of products $B_c^T p_c B_c$ and $B_c^T p_c c$ towards the normal equations (4) using an appropriate weight p_c derived from the estimated variance of the constraining information.

As long as the constraints refer directly to orientation parameters g_o the constraint matrix B_c, values c and weights p_c are easy to specify and enter from the terminal directly in the process of measurements and computations, i.e. in an interactive mode. The operator can modify his approach to the solution by changing the conditions and weight of the constraining information as it suits the case.

If the constraint is linear the operator enters the required information with no special preparations needed. For instance, to express the fact that the photogrammetric base is horizontal in a close-range setup, the constraint is formulated, in the aerial mode notation, by $F_c \equiv b_y = 0$. The corresponding values to be entered are

$$B_c = (0\ -1\ \ 0\ \ 0\ \ 1\ \ 0\ \ldots.\ 0) \quad , \quad c = 0 \quad , \quad p_c = \frac{1}{\sigma_b^2} \quad ,$$

provided that the sequence of orientation elements in vector g_o starts with X,Y,Z coordinates for the left and right projection centres.

A non-linear constraint among orientation elements is handled in a similar way, but instead of unities one must enter the correct partial derivatives in B_c. Constraints using model coordinates are more complex to formulate, may require special programming and, consequently, are not suitable for the interactive operation expected to be set up from the terminal.

Example of Interactive Close-Range Solution

The NRC ANAPLOT (Jaksic, 1979) is an on-line photogrammetric system controlled by the PDP 11/45 minicomputer and supported by extensive software for all basic photogrammetric tasks. A general orientation program for a single model was developed with a particular emphasis on its use in close-range photogrammetry.

In accordance with the principles outlined above, the orientation can be easily modified to fit the conditions of a given photogrammetric setup. This is achieved by a direct operator-computer interaction at execution time. The program accomodates any photoscale and a variable number of unknown orientation parameters. The basic solution yields the complete exterior orientation of two photographs with a total of 12 unknowns. It can be extended to provide the calibration of interior orientation with three additional parameters common to both photographs, or with three independent parameters for each of the photographs. The maximum number of unknowns is then 18. The number of parameters can also be reduced by choosing a simplified orientation that has certain elements preset to given values. An extreme case is represented by relative orientation with five unknown parameters.

The information defining the unknowns to be included in the solution is communicated to the computer by means of a binary string of zeros or unities in a total of nine positions assigned in a standard way to individual orientation elements. The string is used in the computations as a mask to compress or expand the vectors and matrices of the solution in an appropriate manner.

The orientation can also be controlled by additional arbitrary conditions constraining any of the 18 unknowns. Because the constraints have to be entered at execution time, their formulation is restricted to linear forms. The operator enters the weight of the constraint, its numerical value and the coefficient vector associated with the constrained parameters. The program can accomodate up to seven constraints of two different types. The operator can either assign specific values to certain parameters and to their combinations, or require a specific ratio of some computed values.

The measurements are taken in an arbitrary sequence of points and the model reconstruction is usually supported by a number of control points. The operator identifies each point by entering its code or number and by specifying the corresponding control support in a special code. Code '3' means that all three object coordinates are available, code '2' denotes the X,Y support, code '1' indicates that only elevation Z is known and zero code shows no control support available at all. Obviously, the combination of the control support and of the constraint formulation must provide a minimum of information needed to avoid singular solutions.

```
SPECIFY MODEL - SCALE - F - MASK
 F-1 F-2 1, 150000, 000000111

ADDITIONAL CONSTRAINTS? YES

HOW MANY? 1

ENTER WEIGHT - VALUE - MATRIX
100, 100.05, -1,0,0, 0,0,0, 0,0,0, 1

ENTER POINT NUMBER - SPECIFY CONTROL SUPPORT
  11 3
  13 3
  21 0
  23 0
  31 3
  33 3

PARAMETERS

          X         Y         Z          DX      DY        F
F-1    99.976   199.998   249.993     0.000   0.000   150.000
F-2   200.026   199.998   249.992     0.000   0.000   150.000


0.999747  0.010003 -0.020140    0.997941 -0.039986  0.050148
-0.009396  0.999506  0.029993    0.042975  0.997272 -0.060010
0.020430 -0.029796  0.999347   -0.047611  0.062041  0.996937


MODEL COORDINATES AND DISCREPANCIES.....  PHOTO DISCREPANCIES....

PT          X          Y          Z        PY    VPY  VXL  VYL  VXR  VYR
11     100.00     300.00     100.00   -0.01     9    3    5    0   -4
         0.00       0.01       0.00
13     200.00     300.00     100.00    0.01    -9   -1   -4   -3    4
        -0.00      -0.01       0.00
21     100.00     200.00     100.00    0.00     0    0    0    0    0
23     200.00     200.00     100.00   -0.00     0    0    0    0    0
31     100.00     100.00     100.00    0.01    -8    3   -5    0    3
         0.00      -0.01       0.00
33     200.00     100.00     100.00   -0.01     9    0    4   -3   -5
        -0.00       0.01       0.00


REDUNDANCY =  7
STANDARD UNIT ERROR =   5.7 MICRONS

STANDARD ERRORS OF UNKNOWNS

  XC       YC       ZC       KPPA      PHI      OME
0.0094   0.0151   0.0053   0.0000   0.0001   0.0001
0.0094   0.0151   0.0053   0.0000   0.0001   0.0001
```

Fig. 1 Model orientation with base constraint

The program is used in near real-time mode after the condition initialization by the operator. The conversation proceeds from the keyboard of the computer terminal. The computer invites the operator to provide required information in a series of steps, as shown in Figure 1 which documents the solution of a base-constrained model computed from grid measurements in aerial mode at 1:1 scale. In this example, the first instruction identifies the photographs as F-1 and F-2, gives the scale factor 1 for the model computation, the principal distance f = 150 mm, and a nine digit string specifying the type of orientation. Here, zeros denote the unknowns to be retained in the solutions and code '1' indicates the parameters that are to be omitted from the solution. The string is coded in a standard sequence: X_c, Y_c, Z_c, κ, ϕ, ω, dx', dy', df , representing three groups of three values each, for the position of the projection centre, for the rotation elements and for the elements of interior orientation, respectively. In the example, full 12-parameter orientation is required; the calibration elements are not computed. Next a single constraint is defined by determining the photogrammetric base, $b = 100.05$ mm, associated with a weight $p = 100$. The first 10 values of the coefficient vector are given and the remaining eight zeros are truncated. The encoded constraint can be interpreted as ${}^2X_c - {}^1X_c = 100.05$. The following information specifies four of the measured points, numbers 11, 13, 31 and 33, as supported by all three object coordinates whereas points 21 and 23 are used without any control support just for intersection. Since the constraint weight was assigned high, the final base enforcement is absolute, as obvious from the comparison of the projection centre coordinates. A series of additional examples showing the potential of the interactive constraining is presented by Kratky (1979a).

REAL-TIME ELEMENTS IN ON-LINE SYSTEMS

Closed loop on-line photogrammetric systems already contain some elements of real-time processing. To generate an analog motion by an aparently smooth digital control of discrete image positions implies that the calculation of these positions, and their servo-implementation, should not exceed a cycle time of about 20 ms. At this frequency the resulting positioning has a character of a real-time operation. However, the meaning of the calculation performed is limited to a model-to-image projection, which is a very elementary operation in the context of the whole photogrammetric task. Thus, the real-time character of an on-line system is here restricted to the support of a needed hardware function used only as a means to collect measurements and to maintain computer control of the optical stereomodel. As such, it is not a photogrammetric operation which is implemented in real time, but merely a supporting service routine.

REAL-TIME PHOTOGRAMMETRY

One can characterize the role of photogrammetry in some technical fields as a method of positioning. This is often used in stationary or low-frequency dynamic situations. It is customary to measure in single or stereo images, and derive the unknown position of the whole object or of its parts by standard off-line methods which involve an appreciable time delay. Under suitable conditions close-range photogrammetry can be expanded into areas in which the derived three-dimensional information is part of closed loop monitoring systems, or even provides a feedback for automatic guidance and control systems. The difficulty is that in these instances the physical reality to be controlled is usually highly dynamic and the solution is needed with a minimum delay. Information from images must be derived and then automatically processed before it is used in the feedback, or before the next images in the series are available. In other words, the images must be acquired and temporarily retained with the use of non-photographic means, and the identification of important details, as well as their measurement must proceed in automatic mode. Two successful experiments have recently been reported on the use of real-time photogrammetry:

- in biomedicine for continuous measurement of human movement (Woltring, 1977), and
- in engineering for three-dimensional control of dynamic operations (Pinkney 1978, Kratky 1979b).

The most important aspects of these applications are briefly reviewed in the following sections.

Measurement of Human Movement

The study of human movement traditionally relied on non-contacting kinesiological methods of photographic and cinematographic recordings combined with additional sensing devices. In most instances the evaluation was limited to a relatively simple two-dimensional analysis from a single source. Three-dimensional reconstructions eventually introduced stereophotogrammetry as a method, but unfortunately, its potential remained limited due to the tedious manual mode of measurements and also due to the high number of individual models involved. Until recently, hardware and software developments proceeded rather independently. Current trends in signal processing and computer technology, however, indicate promissing possibilities of a real-time coordination and full automation of some approaches. Woltring (1977) thoroughly analyzed the potential of stereophotogrammetry in connection with a new hardware development and advanced data processing. He experimented with a system which incorporates fully automated data acquisition and reduction, utilizing a real-time feedback during the operations. The main principle applied can be described as a multiple light spot sensing, in which a number of small infrared light emitting diodes (LED) attached to a body in positions important for the study, is monitored by sensors directly yielding position dependent output signals. The sensors form parts of two cameras which allow a three-dimensional reconstruction of targeted object points and a real-time digital evaluation of a limited number of spatial trajectories. The cameras are calibrated in a rigorous photogrammetric procedure.

The infrared LEDs are very good point sources, have small dimensions and a fast switching time of less than 1 µs, which allows for a convenient time multiplexing. The sensors are silicon photodiodes in a tetra-lateral arrangement. If their semiconducting surface is non-uniformly illuminated, a lateral photo-effect causes the observed potential to vary with the incident light distribution (Woltring, 1975). The output currents are determined in the resistive path affected by a distinct light spot position, and interpreted as planar coordinates. The settling time for the output is in the order of 30 µs.

In the experimental system developed by Woltring (1974) the detector output signals are fed directly into a minicomputer which can simultaneously process input from three LEDs in a photogrammetric reconstruction. Woltring reports that the resolution can be up to $1{:}10^4$ per axis, with nonlinearities below 1%. The system, though not fully developed, gives a promise of the real-time investigation of human motion in a continuous mode with digital and graphical representations available immediately.

Spatial Control of Dynamic Operations in Engineering

A real-time three-dimensional control was developed at the National Research Council of Canada (NRC) in a combination of photogrammetry, closed-cicuit video sampling techniques and digital processing hardware. The project stemmed from Canada's participation in the U.S. Space Shuttle program, in which the NRC and Canadian industry are developing the Remote Manipulator System (RMS) for the orbiter designed to transport a variety of payloads into Earth orbit. The payload is placed in a large cargo bay and can later be deployed or retrieved by the RMS over a distance of 15 m. In order to deploy or retrieve a satellite, it is necessary to position the RMS end effector within a few centimetres of a grapple fixture on the satellite. The satellite can then be connected rigidly to the end effector and manipulated by an operator. The operation is monitored by means of a TV camera mounted on the RMS. The operator's ability to guide the end effector is thus limited by the fact that the visual presentation on the TV monitor is only in two dimensions. The TV camera can be used for the RMS control directly by employing its image in a photogrammetric resection, which determines the relative camera-object position and attitude, provided that the object is a rigid body and carries a minimum of three control points. The method was demonstrated in real-time, using the equivalent of the orbiter closed-circuit TV camera and on-board computer.

General geometric conditions for the spatial control of the RMS from information collected by the video camera are illustrated in Figure 2. The extended manipulator must be operated in a way to superimpose the end effector E with the satellite grappling hardware represented in Figure 2 by point G. Video camera C mounted close to E is aimed in the general direction to the satellite. In this orientation it can relay images of auxiliary control points targeted on the satellite surface.

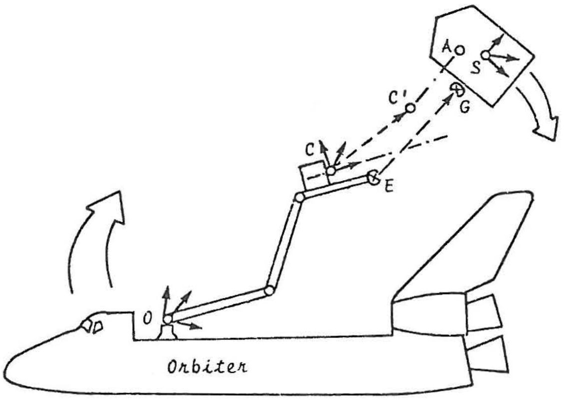

Fig. 2 Function of the Remote Manipulator System

One can derive the six-degree-of-freedom information on the current separation E-G by the photogrammetric resection of the video camera from control points given in the reference system S. For a successful docking, one has to bring the camera into its final position and attitude marked by C'.

An individual resection is only one of a series of processes in which data input, computations and data feedback return must be arranged in a fast cycle, the duration of which is limited by the 30 Hz video scanning process. Manual operations in photogrammetric measurements are not acceptable and data acquisition must be automated. In the NRC project this has been solved by special on-line hardware providing a continuous computer tracking of target images in the video scan as described by Pinkney (1978). Once identified on the TV monitor screen by the operator, the target images are locked onto by the hardware, and the on-board minicomputer will supply information on the position of the target centroids within the video scan. This position is then interpreted in terms of x', y' coordinates defined in the plane of the original optical image.

The computation proper must proceed fast enough to comply with the time limits of the video scanning process and with the capability of the on-board minicomputer, which is of the PDP-11 family. Consequently, one does not consider a fully rigorous solution. Strictly speaking the delays in the response of servos, and inertia of the masses involved make it practically impossible to introduce corrections in the control process at the required time. A non-iterative, approximate solution using explicit formulas, is then adequate to provide valid information for the control feedback. Its accuracy and efficiency increase with the reduced satellite distance. Thus, the photogrammetric control of a dynamic positioning operation in three dimensions is, in effect, self-refining.

The resection is applied in the configuration of four control points positioned as corners in a square figure. This is the minimum configuration allowing for the least squares solution and yielding the corrections to each of the orientation elements in a simple explicit form derived by Kratky (1979b). The computer time consumption for a single frame evaluation is less than 3 ms, which is about 10% of the time available for handling of a single video frame.

The resection computation provides values representing a momentary position and attitude of the video camera in the reference system of the satellite. Each of the six degrees of freedom of the camera is monitored and controlled independently. Each individual C'-C component of Figure 2 is regarded as an error to be eliminated by a suitable correction in the opposite direction. Neither the camera nor the satellite are stationary, but move initially at constant velocities. Without any control action they would gradually drift away as shown in Figure 3, for a single element, by a straight line. A correction can obviously be applied by a momentary deceleration, which gradually suppresses the errors and present velocities.

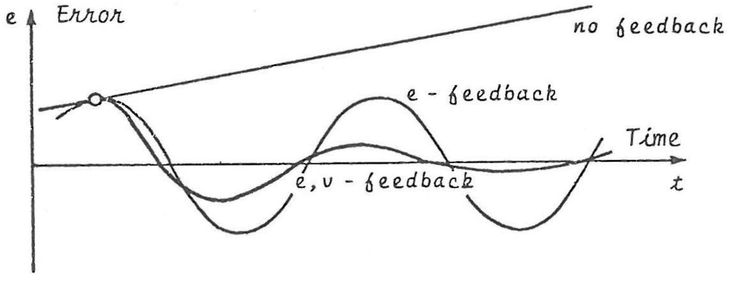

Fig. 3 Position errors of the end effector

To generate a restoring force in the control system, the amount of correction should be dependent on the current magnitude of error e. This arrangement gives rise to a harmonic motion, in which error e varies sinusoidally with time (Figure 3). A suitable damping can be achieved by making the correction also dependent on the current error velocity v. Photogrammetrically determined values of current errors e and velocities v are used to compute and introduce negative acceleration a, which controls the errors in a damped oscillation mode

$$a = -(k^2 + \omega^2)e - 2kv \tag{8}$$

Angular frequency ω is derived from the desired period of oscillation, and coefficient k is a function of the selected damping power.

The electronic distortion typical of TV imaging systems is not critical, because image coordinates are determined by digital operations in the video scan and not affected by the quality of the final optical display on the monitor screen. In laboratory experiments with the on-line video scanning processor the geometric stability of a video scan was maintained within 5 μm in the video image frame of 25×25 mm (Pinkney, 1978).

The control operation starts when the RMS end effector is brought under manual control to a distance of about 3 m from the satellite grappling mechanism. Since the camera is located about 1 m back from the end effector, the operational range of the camera is between 4 and 1 m. Extensive simulations and laboratory experiments at the NRC proved that the control process converges within 200 to 300 iterations (7 to 10 s), even if the errors of the video output were artificially increased up to 100 μm. The final position of the end effector is controlled within 5 mm and the attitude within 5 mrad from the expected destination.

The technique has a general potential in all dynamic engineering tasks where the real-time aspect and remote control are crucial to the operation. Besides obvious space applications these may be, e.g., manipulations in nuclear laboratories and power plants, special technical operations performed underwater and also automatic docking manoeuvres of supertankers.

CONCLUSIONS

On-line photogrammetric systems offer a versatile control of close-range photogrammetric tasks. Both the accuracy and economy of model reconstructions benefit from the operator-system interaction, which allows for a change of conditions and even for a modification of the photogrammetric formulation if needed.

In order to utilize real-time solutions in close-range photogrammetry it is crucial to apply non-photographic techniques in analyzing optical images for an automated identification of details and immediate processing of related measurements. First steps in automated photogrammetric monitoring and control of dynamic three-dimensional operations have successfuly been made in biomedicine and space engineering. Both tested techniques give a good promise of becoming routine real-time applications of photogrammetry.

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