

A NEW MS-DOS BASED INTEGRATED SOFTWARE PACKAGE FOR TRIANGULATION AND DATA COLLECTION FOR CLOSE RANGE APPLICATIONS

Dr.-Ing. Ludger Hinsken
C&H Photogrammetry
Ringstr. 79
D-7750 Konstanz 19
Germany

Luis Cogan
C&H Photogrammetry
Weiherstr. 2
CH-5015 Niedererlinsbach
Switzerland

Dr.-Ing. Rüdiger Kotowski
K² Photogrammetry
Planckstr. 51
D-7000 Stuttgart 1
Germany

Abstract

The new software package integrates the on-line connection to an analytical instrument and the triangulation process under a common user interface. The triangulation is based on the well proven close range bundle adjustment package CAP. A consistent data flow between the individual components of the new package is assured. For easy handling of the processed data the package provides graphical feedback. The package consists of various modules which can be combined to a best suitable package for the user's needs.

1. INTRODUCTION

Analytical plotters with 9"x9" photo stages are primarily targeted to the map making market producing maps from aerial photographs. Therefore numerous software packages for this type of applications which are highly optimized for this task are available since years. But as everybody knows the analytical instrument is not limited to aerial applications it can also be used for close range applications. What is basically needed to use every analytical instrument for close range applications is appropriate software.

In this context two groups of programs are relevant. First, the Real-Time-Program which drives the analytical instrument and second, the photogrammetric application programs which perform the measuring and orientation tasks. Existing solutions (Fuchs, Leberl, 1984; Dueholm, 1990; Knopp, 1990) are often based on an extended Real-Time-Program to make it suitable for close range requirements. The photogrammetric application software which runs on a separate computer is closely coupled to the Real-Time-Program. These application programs do the simultaneous handling of several models on two photo stages and the proper mathematical modelling of non-metric close range cameras. To gain precise results in close range applications a bundle adjustment program is required. The existing software packages usually provide an orientation by bundle method.

With the appearance of new types of Real-Time-Programs such as the Leica Mapping Terminal (LMT) (Cogan, Hinsken, 1992) the situation for close range applications has changed. This program is capable of already handling the basic requirements for close range applications. It features an own user interface which allows the user to change parameters such as the assignment of the encoder axes and the encoder resolution. Furthermore the LMT can handle multiple models at the same time. Provision for handling of non-metric cameras and reseau corrections are given.

Based on such a type of Real-Time-Program the photogrammetric application program can concentrate on the measuring and bundle orientation process.

With the decision to provide close range photogrammetric software on MS-DOS based Personal Computers the amount of software available from other disciplines is practically unlimited. Once the orientation parameters are computed by bundle adjustment and transmitted afterwards into the analytical instrument the user can use the application software of his own choice. There are various software packages available in the market which fulfill the needs of a 3D data acquisition program. Usually these are CAD packages such as AutoCAD or Microstation or other vendors.

Bundle adjustment is an important tool in photogrammetric work. It is used primarily to transform all data into a common coordinate system. The bundle adjustment itself is surrounded by two other steps in the photogrammetric working process. Before the adjustment can be carried out, measurements of image coordinates need to be made. After the adjustment program has been run, the results of the adjustment need to be analyzed. For the user it is very important that the three working steps, namely measurement, adjustment and analysis work as close together as possible. This will insure maximum efficiency in his day to day work.

The newly developed software package MAAS-CR which is the short form for: Measurement Adjustment and Analysis Software for Close Range puts together these three important steps of photogrammetric work.

The paper will describe the functionality of one module of each group. It will explain one of the measuring programs, the bundle adjustment program and the graphical analysis program. The remaining programs of the package are only noted very briefly for completeness.

2. MAJOR COMPONENTS OF MAAS-CR

MAAS-CR consists of the following major software modules:

2.0.1. DATMAN : Data Management

This group of programs manages following types of data:

- Project related data
- Object control data
- Camera related data

This group of programs are interactive full screen editing programs and file handling programs.

2.0.2. MODMAN : Model Management

This group of programs handles stereo model related data. They perform the measuring task, adjustment and analysis of stereo models in conjunction with the measuring instrument. Following orientation programs belong to this group:

- Inner orientation
- Relative orientation
- Absolute orientation

2.0.3. DATRI : Data capture for Triangulation

This program is used to perform the measurements required to make a bundle adjustment afterwards. It includes the necessary orientation programs and proper handling of reseau information. Besides the collection of observations this program will also deliver initial values of exterior orientations of the measured images which will be used as input data for the bundle adjustment.

2.0.4. PRIORI : Preorientation Programs

In close range applications it often happens that the information collected during the measuring process is not sufficient to go directly to the bundle adjustment step. If this is the case programs are needed to fill the gap. These programs are used to calculate initial values for the bundle adjustment which were not already provided by the measuring programs. These programs use relative and absolute orientations to generate the required approximate values in a common coordinate system. They use special algorithms, singularity free relative and absolute orientation along with a space resection program, to solve the approximate value problem (Hinsken, 1987). But with integration of measurement and bundle adjustment software into one package it is the aim to skip this step totally, because the result of DATRI should be sufficient to start the bundle adjustment immediately.

2.0.5. CAP : Combined Adjustment Program

For close range applications CAP is integrated in a special version into the package. It comes with specially adapted interfaces to the measuring and analysis programs.

2.0.6. GRAV : Graphical View

This program provides extensive analysis features for the results of the bundle adjustment. It is highly interactive with the user, so he can see the results in various forms.

2.0.7. TOP : Transfer of Orientation Parameters

This module is used to extract individual models from the results of the bundle adjustment. It transforms the exterior orientation parameters into a suitable form for the connected measuring instrument and transmits the transformed parameters into the measuring instrument. After this step the operator can start with data collection in a parallax free model based on bundle adjustment.

3. MEASUREMENTS

In this context only those measurements are considered which are required to measure the necessary points for bundle adjustment. Furthermore it is assumed that measurements are performed on an analytical plotter, which is nowadays standard device for precise photogrammetric measurements. The analytical plotter is assumed, because it is considered, that after triangulation the images will be further processed in an analytical plotter. Measuring the images with stereoscopic viewing. For this further processing the orientation parameters computed by the bundle program will be used in the analytical machine to form the stereo model.

3.1. Measuring Programs

The measuring programs are directly connected to the measuring device. During the measuring process the operator is guided by the programs. All programs use the same user interface. Whenever it is useful the feedback to the operator is given in graphical form. Presenting results of measurements and adjustment in graphical form allows the operator to find remaining systematic effects and measuring errors much faster compared to the presentation in list oriented form. This holds true especially if the amount of data is huge.

3.2. Inner Orientation

The photogrammetric observations which serve as input to a bundle adjustment program are image coordinates. The image coordinates refer to the image coordinate system which is usually given by fiducial marks or reseau crosses. In any case a physical reference system must be established inside of the camera body. As measurements are carried out in a measuring device related coordinate system a transformation from measuring device to image coordinate system must be done before the bundle adjustment can be performed. This type of transformation is usually called inner orientation. The mathematical model used for this transformation depends on the camera used and the accuracy required for the project. If there are only fiducial marks on the peripheral of the image format nothing better than a global transformation between the two systems is reasonable. If the camera is equipped with a reseau a local transformation for

each individual mesh can be applied. This leads to a much better modelling of film deformations. The reseau correction is image related and not camera specific. This means that the effect of local film deformation is modelled by the inner orientation and not by the bundle adjustment. Furthermore the film deformation varies with time, temperature and humidity. But all these effects can be properly modelled by use of a reseau and be eliminated by the inner orientation.

During a photogrammetric project the inner orientation program is used very often. After the film has been placed on the stages, the inner orientation program will guide the operator through the whole measuring process. The program will drive to predefined locations and wait until the operator has measured the point. Depending on the amount of measurements already made, the distribution of points in the image and the preselected type of transformation the program will constantly compute as many transformation parameters as possible with the current set of data. The user interface will keep the operator informed about the status of the measuring process. He can see the points already measured the ones still to be measured distinguished by shape and color. This feature is mainly of interest for reseau measurements. Furthermore the residuals after the transformation are displayed on the screen for inspection by the skilled operator. The user interface of the measuring programs looks very much the same as of the examples given in chap. 5.

At any time the operator can interact with the program through the graphical user interface. He can mark points to be excluded from the adjustment of inner orientation parameters or need to be remeasured. Also he can change the type of transformation at any time.

After measurement and adjustment of inner orientation has been finished, the operator will accept the result, which will then be transmitted to the analytical plotter for further use.

3.2.1. Measurement of Reseau before Triangulation

As the reseau correction is image related, it needs to be repeated each time the image was removed from the measuring instrument. To save time during the measuring process only those points should be measured which are really required for the current purpose. Triangulation is a process which works pointwise. That means there is no information needed in between two points. Therefore the measurement of the reseau can be limited only to those meshes which surround the points used in the triangulation process.

3.2.2. Measurement of Reseau after Triangulation

After the bundle adjustment has been carried out and the images have been put back into the machine, the inner orientation needs to be redone. But in case of a reseau camera now only those crosses need to be measured which cover the area of interest. It might happen that the crosses to be measured do not match the ones used for triangulation. But this is not important. As the operator wants to drive

through a parallax free model after bundle adjustment, these reseau corrections need to be transmitted into the analytical plotter for on-line correction of film deformations. If the operator doesn't know in advance exactly which area he will use later on he can measure the whole reseau, which will also take a few minutes on an analytical instrument only.

If the operator wants to do selective measurements of the reseau the graphical user interface makes it very easy to select the area of interest. After the selection the program will guide the operator through the measuring process.

4. BUNDLE ADJUSTMENT

Traditional bundle programs for aerial applications are optimized for the aerial case and also based on assumptions concerning the block geometry. The process of taken photographs for map making is highly standardized. The bundle programs can rely very much on the assumption that photographs were taken according to the standard situation. Typically a block is formed by strips with regular overlap within strips and between neighboring strips. The geometry is quite simple, because usually the image plane is parallel to the object surface. The types of observations in aerial case are normally limited to image coordinates and coordinates of control points.

However the situation in close range applications is quite different compared to the aerial case. In close range applications, specially in industrial applications, the geometry of a block varies from project to project. The types of observations used in close range applications include also geodetic observations like distances besides the normal photogrammetric observations. Furthermore as the cameras used in close range applications are quite different compared to aerial cameras, the cameras very often need to be modelled in a certain way. As the block geometry isn't standardized as in the aerial case, prediction of accuracy in the object becomes more difficult.

This type of applications requires a specialized bundle program to fulfill the various requirements.

4.1. CAP

CAP (Combined Adjustment Program) is a bundle adjustment program which was specially designed to fulfill the needs of close range applications.

4.1.1. Types of Observations

CAP is capable of handling following types of observations:

- image coordinates
- model coordinates
- spatial distances
- horizontal distances
- directly observed coordinates (weighted control points)
- coordinate differences (height differences)

- horizontal, vertical directions in object coordinate system
- horizontal, vertical directions in a theodolite system
- camera parameters
- exterior orientation parameters of images
- exterior orientation parameters of theodolites
- model orientation parameters

4.1.2. Parameters

The primary task of bundle program is to estimate object coordinates and exterior orientation parameters. The functional model between object coordinates and image coordinates is the well known perspective transformation (Brown, 1974). In close range applications the parameterization of the rotation parameters is very important, because the chance is quite high, that some of the rotation parameters become undeterminable. This would lead to the situation that the whole normal equation system becomes ill conditioned and the results of the estimation process cannot be obtained. If a bundle program has no special feature to handle this case either the program would stop or in the worst case it would produce wrong results. CAP utilizes a special estimation technique for rotation parameters (Hinsken, 1987; Pope, 1970). This estimation technique combined with a special algebraic parameterization of the rotation parameters (Schut, 1958/59) ensures that CAP cannot have any singularity problems due to the rotation parameters. Another effect of use of this technique is, that it requires minimum effort to compute the necessary numerical coefficients during the iteration process. In close range applications where there might be lots of observations per image this results to an overall acceleration of the adjustment process.

For precise measurements in photogrammetry the camera parameters cannot be considered to be known with sufficient accuracy beforehand. Therefore the bundle program has to consider the camera parameters as unknown parameters. CAP provides various parameters to model the camera. It is also possible to handle multiple cameras during one bundle adjustment. For extreme cases it is possible to assign each image a new individual camera. This is required for special applications with so called high speed drum cameras (Godding, 1990). Following parameters can be calibrated by CAP:

- principal distance
- coordinates of principal point
- radial symmetric distortion (also dependent from distance between object and projection center)
- asymmetric and tangential distortion
- affinity and non orthogonality
- unflatness of vacuum platen
- irregular film deformations

Altogether 21 parameters can be successively selected to describe the used camera. The so called additional parameters used in CAP are described in more detail in (Brown, 1976). The availability of

the additional camera parameters makes it possible that CAP can be used as a special calibration tool for cameras. The types of cameras which can be described by the implemented camera model range from aerial cameras (Ellenbeck, Peters, 1989), large format close range cameras (Dold, 1990), medium and small format film based cameras (Peipe, 1990; Wester-Ebbinghaus, 1986), down to smaller format CCD cameras (Bösemann, Godding, Riechmann, 1990). As it sometimes might be difficult for the unexperienced user to perform a so called on the job calibration, the camera model is implemented in a manner that also unexperienced users can get appropriate results. A basic difficulty with on the job calibration is the determinableness of the selected parameters. In estimation technique this problem is known as over and under parameterization. While under parameterization usually leads to non optimal results, over parameterization causes so called configuration defects. This means that the whole adjustment system would become ill conditioned and would therefore deliver wrong results. To avoid this problem CAP utilizes special weighting technique of the camera parameters, so the program will always deliver reliable results. Nevertheless the experienced user is allowed to disable the protection features.

4.1.3. Datum Definition

A very important aspect for close range application is the definition of the datum of the object coordinate system. Under this topic CAP offers four ways of defining the datum.

- error free control points
- control points with given accuracy
- exterior orientation parameters with given accuracy
- free net adjustment

Error free control points don't participate in the adjustment they only define an error free datum.

Control points with given accuracy participate in the adjustment and may be changed in the numerical values dependent on the weight with respect to the accuracy and strength of the image observations and the whole block. The quality of the datum with respect to accuracy depends totally on the quality of the control points.

Rather seldom used but possible is the solution to define the datum by given exterior orientation parameters. This requires the measurement or definition of projection centers with respect to the object system. In case of a theodolite measurement the six exterior orientation elements of the theodolite of one station can be fixed to define the datum. If the theodolite was leveled this would lead to a leveled object coordinate system. The remaining degree of freedom can be fixed by at least one distance measurement.

The most elegant way is to define the datum by an additional minimum constraint. This results in the so called free net adjustment. The block geometry must be strong enough to build a stable three dimensional network. This is usually the case in close

range applications but not in aerial applications. If this requirement is fulfilled the free adjustment will transform the network build from the observations only, without any constraint onto the initial values of selected object points. This results in an error free datum of very high quality. The extremely high quality can be proofed by the resulting error ellipsoids on the object points. They become smaller than with any other kind of datum definition.

4.1.4. Algorithmic Aspects

To gain high performance of a bundle program the selected numerical algorithms are essential. Typical for combined adjustment is a not regularly structured normal equation system, in contrast to the regular structure of an aerial block adjustment. As the number of unknowns in bundle adjustments is usually quite high, the normal equation system is a sparse matrix. Special algorithms for general sparse matrices exist (George, Liu, 1981). After various empirical tests (Hinsken, 1985), the best suitable algorithm of that class was modified and implemented in CAP. This algorithm requires the minimum amount of computer memory to store the normal equation system. The storage technique doesn't store any zero elements. Before the numerical adjustment is performed a logical computation takes place which figures out, in which position of the normal equation system non zero elements will appear during the numerical computations. Besides the minimum storage requirements and minimum computation time it ensures also, that round off errors are reduced, because less numerical operations are performed.

As the non zero structure of the normal equation system depends on the ordering of the unknown parameters in the equation system, CAP uses a reordering algorithm to find the best order of unknowns in the equation system. This is not a trivial problem in combined adjustments. However the numerical results are not effected by the order of the unknowns. The implemented reordering algorithm is the so called Banker's algorithm (Snay, 1976). The aim of the algorithm is to reduce the amount of computations during the numerical handling of the normal equation system.

Furthermore the fastest known algorithm to invert a sparse matrix is implemented in CAP (Hanson, 1978). This special algorithm inverts the matrix only at those positions where non zero elements were located by the preprocessing logical algorithm. This allows for full error propagation for unknowns and functions of unknowns (e.g. observations).

4.1.5. Statistical Model

The implemented numerical algorithms were selected in such a way that full statistical error propagation can be performed. This is an important feature for industrial applications.

The following statistical values are provided in the output file:

- standard deviations of object point coordinates

- standard deviations of exterior orientation parameters (image, model, theodolite)
- standard deviations of camera parameters
- standard deviation of adjusted geodetic observations
- local redundancy of all image, model and theodolite observations
- correlation matrices of camera parameters
- correlation matrices of correlation between exterior orientation and camera parameters
- internal reliability of each observation
- single point test statistic for deformation analysis
- variance of unit weight
- variance components of model observations

Furthermore statistical information is provided in separate files:

- covariance matrices of object points (computation of error ellipsoids)
- covariance matrices of projection centers (see above)

To help the user analyzing the results the before mentioned information can be visualized by use of a special graphical analyzing program.

4.1.6. Blunder Detection

The bundle adjustment is based on a least squares adjustment. The results of least squares adjustments are only correct, if the observations are free from gross errors. If this is not the case, the gross errors must be eliminated from the adjustment. If those blunders are not eliminated from the set of observations they cause so called smearing effects on all estimated parameters. Therefore a statistical test is implemented in CAP to detect if the observations contain blunders. The test is performed on residuals which are divided by their respective standard deviation. The computation of the standard deviation of the residuals involves the inverse of the normal equation matrix. Therefore the geometry of the block is included in the blunder detection test (Pope, 1976).

4.1.7. Deformation Analysis

The ability of CAP to perform a free net adjustment leads to another ability namely to analyze deformations on object points. Therefore a single point test statistic is computed. This test value is used to figure out if individual points have changed their coordinates significantly. The normal equation inverse is included in the computation of the test statistic therefore the geometry of the block and also the accuracy is included in the deformation analysis. The deformation analysis is an iterating process. The basic aim is to bring the two object coordinate systems of two different epoches into the same datum. To figure out which points can be used to define the datum, the test statistic is used. The method is used successfully in industry for regular tool inspections and also on huge deformations (e.g. crash tests).

4.1.8. Multi-Media Photogrammetry

Today, bundle triangulation programs are usually based on the functional model of collinearity. The deviations from ideal central projection (e.g. lens distortion, film unflatness and deformations etc.) are modelled by additional image error describing parameters. Such a functional model is usually inappropriate for applications where light-refracting surfaces are located between the object and the projection centers, e.g.:

- under water photogrammetry,
- mapping in shallow water,
- survey of sheltered objects,
- correction for errors generated by reseau plates.

In those cases the functional model must be extended for considering light refracting surfaces (Kotowski, 1987, 1988).

Inspired by practical requirements CAP includes a sophisticated mathematical model for multi-media photogrammetry.

4.1.9. User Interface

CAP is a batch program. Once the program is started the user doesn't need to interact any more with the adjustment program. But he is constantly informed on the computers screen about the current status of the program.

4.1.10. Performance of CAP

To give an impression of the over all performance of the algorithms implemented in CAP the table 1 below shows some results of computation times of projects of various size. The over all computation times include finding the adjacency structure of the block, solving the least squares adjustment by Newton Gauss method, computation of the inverse of the normal equation matrix, computation of all statistical values and saving all results to output files.

Example:	A	B	C	D	E
# Obj. Points	198	58	502	216	84
# Images	13	12	17	24	38
# Geod. Observ.	7	17	44	23	5
# Camera Params.	5	5	5	5	5
# Unknowns	684	257	1,613	803	492
Total Redundancy	1,497	744	1,963	2,050	1,015
# Iterations	6	5	4	4	5
Time [sec]	220	108	284	354	436

Table 1: Performance of CAP

All numerical computations were carried out on a Compaq 386/20e which was equipped with a 80387 math coprocessor.

5. ANALYSIS OF ADJUSTMENT RESULTS

Besides the standard ASCII file output created by CAP there exists a special interface to exchange data with the analysis program GRAV.

GRAV is a highly interactive program. When the program is started it will automatically retrieve the data of the last bundle adjustment. The first view provides the user the object coordinates and locations of projection centers in the X-Y plane of the object coordinate system. The example used throughout this chapter shows an object in the center of the field of view and the projection center locations around the whole object.

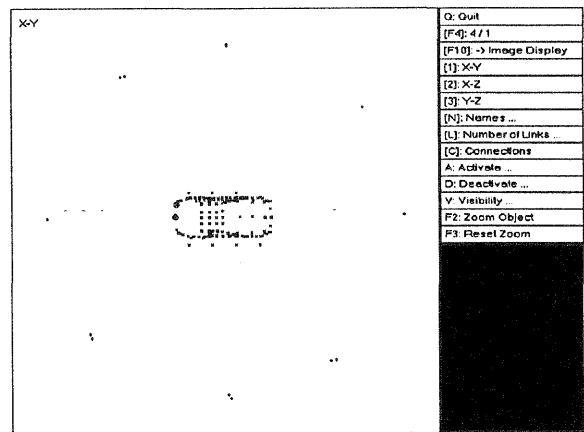


Figure 1: Object and projection centers in X-Y plane.

The user can view the object from any coordinate plane. For better overview the point and image numbers can be displayed selectively. To distinguish between different types of object points and projection centers the user can define color, shape and size of any type which is displayed. On a color monitor this makes the analysis of the results very convenient.

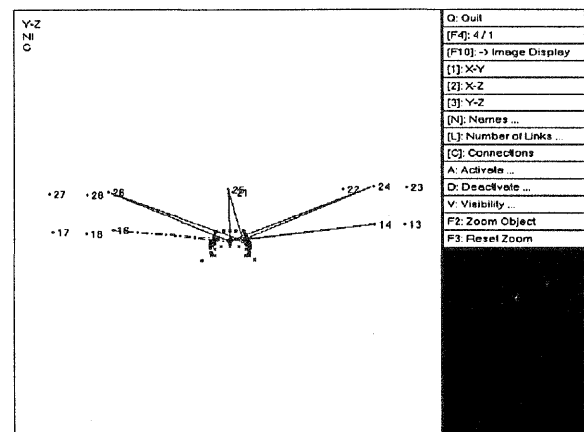


Figure 2: Display of object in Y-Z plane. Image numbers activated and some rays from images to object points.

The upper left corner of the display region displays some status informations. This view shows that the images were taken from two height levels.

A very useful feature for comparison of points of interest is the so called split frame mode. In this mode the display region is subdivided into four small windows. Each of the windows can display

different informations from the same bundle adjustment.

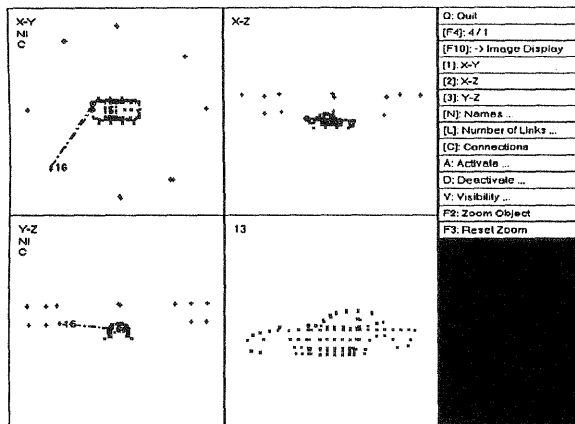


Figure 3: Display in split frame mode.

At the same time the user can see the object and the locations of the projection centers in three different coordinate planes. The fourth window displays image number 13. Here the point distribution of that image can be seen very well.

The display of image information can also be used on the large display.

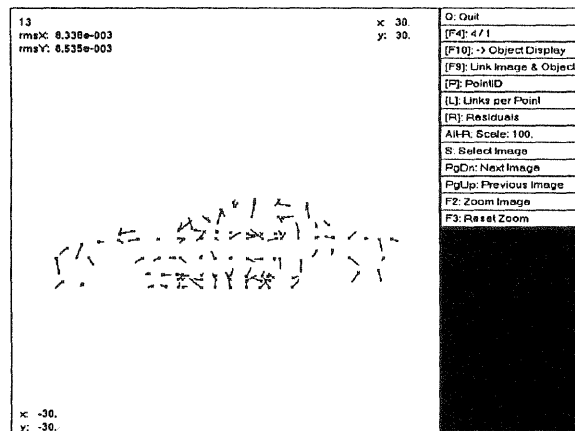


Figure 4: Display of single image with residuals in big frame.

In the upper left corner the image number and the rms values for x and y residuals are displayed. The color, shape and size of the image points correspond to the type of points in the object. Residuals are displayed in the corresponding color too. This is very helpful for the analysis of the residuals. Blunders which are not contained in this image are also marked with a special color. Additionally those points are surrounded by an extra circle.

To analyze the results in more detail, the display can be zoomed at any time.

The few examples given in this chapter should demonstrate already the advantages of using graphic for the analysis of bundle adjustment results.

6. TRANSFER OF ORIENTATION PARAMETERS INTO MEASURING INSTRUMENT

After bundle adjustment and analysis have been finished the computed exterior and camera parameters are used to form stereo models. The program TOP provides interfaces to the output files of CAP and a connection to the analytical instrument. The program has to transform the exterior orientation parameters from bundle adjustment into a form which is suitable for the instrument and the operator. The program has to assign a proper orientation and scaling to the model parameters which are transferred to the measuring instrument. With modern types of Real-Time-Programs which drive analytical plotters (e.g. LMT from Leica) it is possible to interchange encoder axes and encoders resolution from the user interface of that program. Furthermore it is possible by use of an integrated additional transformation between input encoders and model to get the encoder movements in any arbitrary orientation without interfering model or object coordinates. This is quite useful for close range applications.

TOP works closely together with the inner orientation program, because the inner orientation of each image needs to be checked or repeated after bundle adjustment (see chap. 3.2.2) before the model parameters are transferred to the instrument. It's also important to mention that in case of on the job camera calibration during bundle adjustment these parameters are transferred into the analytical instrument.

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