DEVELOPMENTS AND CHALLENGES IN BUNDLE TRIANGULATION

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ABSTRACT

During the last decades, bundle triangulation has not been discussed as much as in the earlier years. Algorithms are known and developed, and software packages are available. This paper reflects all requirements and developments in this field during the last 30 years.

In the early years computation formulas and algorithms for simple block adjustments have been discussed. Additional parameters and speed have been as well of high interest. The new techniques of GPS and IMU brought really new challenges to the mathematical model. The idea of direct geo-referencing leaded to the opinion, that bundle adjustment is not necessary in the close future anymore. However, the opposite is the case. With introduction of automatic tie point matching the amount of points and photos has been increased considerably. The error percentage was growing, and manual error elimination was not longer possible. New digital cameras allowed many more images, but they demand serious simultaneous camera calibration if high precision is required. This is especially true for so called "semi-metric" cameras. Furthermore, the amount of data has been increased once more again. Therefore, only numerical presentation of adjustment results does not give a sufficient overview of the results. Graphical presentations are required. For the developments of 3D city-models terrestrial and oblique images have to be processed. Condition between those multi-camera exposures can strengthen the model. Camera calibration is again a very important task. Several software packages for these purposes will be listed. The development steps of the BINGO bundle triangulation software will be shown as an example.

INTRODUCTION

Since 1965 I am in surveying business. At that time we have had mechanical calculators and no idea about electronic data processing. As a student of geodesy in Hamburg I had my first contacts to computers in 1968. It has been an IBM 1130 with 16KB of RAM and a big hard disk with 1 MB storage capacity. I was very proud on my first programs for simple surveying applications. During vacation I worked on a Zuse Z11 in Hamburg's state government.

Only a few years later in 1971 I started a development of a software package to process the data of the first electronic tachymeter RegElta14. The computer system had been a CDC 1604 with punching card input. The closed shop system of the computer center allowed up to three test runs per day. In 1973 we able to transform the punching tapes from the RegElta14 instrument into drawn maps and contour lines – a big step at that time. All programming work had to be done on mainframe computers at that time. A few years later the first pocket calculators came to the market, as well programmable units with very limited capabilities. A simple pocket computer which is now 5 US$ had a price of about 1.000 US$. So we had two parallel developments: Software on mainframe computers and first small programs on mini- and micro-computers (today called workstations) and pocket-computers – as well for simple geodetic applications. The first bundle triangulation programs had been developed as well on mainframe [Brown] and on those micro-computers.

At that time the literature was reporting the formulas for bundle adjustments, solution methods, and the first self-calibration parameters. But these years I did not yet know so much about bundle adjustment. However, 1979 I got a scientist position in the Institute of Photogrammetry an Engineering Surveys under Professor Gottfried Konecny and learned a lot about photogrammetry, close range applications, block adjustment and application programs for block adjustment. I was mainly working in industrial photogrammetry. 1980 I started to develop my own bundle triangulation program – still on a mainframe computer CDC Cyber 73/76, because the available programs were not able to fulfill our requirements. They were not able to process terrestrial images or they were not able to integrate additional object measurements like distances, angles etc.

The main effort was to find a solution algorithm for the normal equation system. The structure of an equation system including additional object information differs considerably from normal equation for standard aerial triangulation. From the years 1980 to 1985 many publications deal with the question how to establish and solve those equation systems [Ebner, Hinsken, Kruck, Wester-Ebbinghaus …]. Sparse techniques replaced the recursive partitioning and band algorithms. Because of the limited computer access, software development was slower then today and much more expensive.

In the years about 1990 to 1995 changes in technology introduced new problems, but also new possibilities.

- The IBM-compatible PCs turned to real workstation computers, and new run-time systems (Windows, Linux) allowed new graphical applications.
- Image scanners conquered the photogrammetric market and images became digital. As a consequence first programs for automatic tie-point matching have been developed. The amount of data for bundle triangulation was growing, but also the error percentage. Automatic error removal was the new challenge.
- Also new systematic image deformation from not well calibrated image scanners had been recognized. Therefore new analysis tools were requested to check image geometry.

In the next years GPS and IMU systems have been combined widely with aerial cameras, and direct geo-referencing has been proposed. The idea was to neglect bundle triangulation completely. Many tests have been made to determine the GPS precision in advance. However, at the end the GPS processing provided in every case unpredictional results. The precision is still depending on many different influences like satellite configuration, atmospheric influences, reference stations, processing software, and as well on the experience of the person at the keyboard. Beside so called shift and drift parameters mathematical rigorous methods have been developed to overcome the GPS problems [Kruck & Wübbena]. Together with an IMU the situation had been considerably enhanced. The IMU data supports the GPS processing. To calibrate the IMU misalignment, bundle triangulation programs had to be extended to estimate the rotational matrix between camera and IMU system (″bore sight calibration″ or better: ″IMU misalignment calibration″, because the camera is not a tank).

With the new century digital aerial survey cameras started to replace the analogue aerial film cameras. Suddenly, on no additional cost many more images have been taken. The overlap changed in many cases from 60% to 80% and the sidelap has been as well increased for better ortho photos. Together with programs for automatic tie-point matching we have suddenly a really huge amount of data to process. Because the digital aerial cameras combine each image from several smaller images which are exposed in the same position, the geometric precision of this combination (stitching) has to be checked and calibrated in case of high precision requirements.

Therefore: For precise geo-referencing, bundle triangulation has to be done to process all the different data and calibrate the systems simultaneously. And it can be done with a minimum of cost, because of the automated processing.

The most important questions in photo geo-referencing are not anymore algorithms but the user interface and error and problem recognition and management. In a block with 5000 photos with 100 measurements per photo, ground control points and GPS and IMU data, it is not possible anymore to view the results only numerically. Graphical support with various possibilities is highly demanded. Furthermore programs have to be stabile and robust. It is necessary to analyze data very intensive and carefully and to report recognized problems. Logical data errors or wrong point or photo numbers have to be detected as well as measurement errors.

Table 1. Short list of bundle triangulation programs available in the market

Albany	CRISP	PAT M43
Australis	GIANT	PAT B
AeroSys AT	ISBBA	Photo G
BINGO	inBlock	Photo T
BLUH	ORIENT	STARS
CRABS	ORIMA	

Many of the listed programs have those features today, but at the end an experienced photogrammetrist should check the block. This is especially true in case of any remaining systematic effects in the image geometry, the GPS/IMU residuals, or control point residuals. As well the block geometry and the photo connections have to be checked. Furthermore the achieved accuracy should be proven – the best with some independent check points.

There is since long time a big demand as well for oblique aerial photos e.g. along coast lines, for slopes in mining industry, and for 3D city modeling. Not many programs can process those images. BINGO can do it easily; because it’s starting point has been close range photogrammetry.

Table 2. As example a list of interesting development steps of the BINGO software:

1981	First small BINGO version for terrestrial photogrammetry on CDC Cyber 76.
1982	Expansion for larger blocks and camera calibration including additional parameters.
1983	Expansion for aerial triangulation. Introduction of Baarda's Data-Snooping. Integration of survey measurements.
1984	Introduction of Variance-component estimation
1985	Installation on Nova Data General and VAX-11
1986	Version for HP-1000 computer and linkage with Planicomp system. Version for blocks with SPOT line scanner images.
1987	Automatic computation of initial orientation data for all photographs: aerial or terrestrial.
1988	Integration of GPS. Versions for Silicon, InterPro, MS-DOS
1996	Introduction of a real free network adjustment (with minimum trace and minimum solution vector). Development of the mathematical rigorous CPAS solution for GPS.
1997	Development of BINGO and BINGO-Tools under Windows NT.
1998	Speed enhancement to allow bigger blocks and more points.
1999	Enhancements of error detection and automatic error elimination.
2000	Integration of IMU observations. New GUI for BINGO and the BINGO Tools.
2001	Enhancements of GPS/IMU processing. Integration into medical systems.
2002	New calibration possibilities for digital cameras with stitched images including calibration of PPS.
2003	Automatic dynamic array allocation. Graphical tool to display image distortion.
2004	Integration into Socet Set. Remote update tool. Introduction of ″standard aerial triangulation″. New graphics and new tools.
2005	Robust transformations in RELAX. New GUI and new graphics. Version for Suse Linux. Integration into AEROoffice. Interactive 3D Viewer for block geometry, residuals, footprints, photo connections and many more.
2006	Speed enhancement. New processing tools to reduce the number of points per image.
2007	New tool to identify missing photo measurements to get more multi-ray points. Support for JAS150 line scanner images.
2008	New graphics to show image residuals and skipped as well as missing measurements
2008	Speed enhancement. Support for multi-head cameras. Unlimited capacity.
2009	New graphics to view GPS/IMU residuals for easier recognition of systematic errors. New tool to export results to other photogrammetric systems.

IMPORTANT DEMANDS FOR BUNDLE SOFTWARE

As founded on fact in the introduction we create a list of very important requirements for modern automated bundle adjustments. These are:

- Automatic estimation of initial orientation data and point coordinates (if no GPS/IMU).
- Automatic error elimination for photo measurements using statistical methods. Robust estimation is not sufficient anymore in all cases.
- Advanced camera calibration techniques.
- Integration into photogrammetric processes for a smooth workflow.
- Advanced problem recognition and problem management. E.g. in case of insufficient block geometry, lack of datum information, over-parameterization, or two parallel rays to one object point should not crash the system, but give clear hints about the problem.

- Graphical presentation of all adjustment results for easy analysis. Together with the problem recognition the graphical presentation is one of the most important points – especially when blocks of several thousand photos have to be processed.
- Processing of terrestrial photos and oblique aerial photos can be combined with standard aerial photos in one bundle adjustment. This is important e.g. for 3D city modeling.

GRAPHICAL PRESENTATION OF ADJUSTMENT RESULTS

In this chapter possibilities and requirements of graphical presentations will be demonstrated with examples from the bundle triangulation package BINGO. This includes currently seven partly very powerful graphical programs. Three of them are viewers only; four of them can output the graphics as well on any printer or plotter or prepare the graphics for text documents. In many projects really curious things have been detected by the graphical programs.

Image Measurements and Image Residuals

Image residuals are expected normal distributed. If they show systematic effects, adjustments results might not fit to reality. The reason for the problems has to be searched and eliminated.

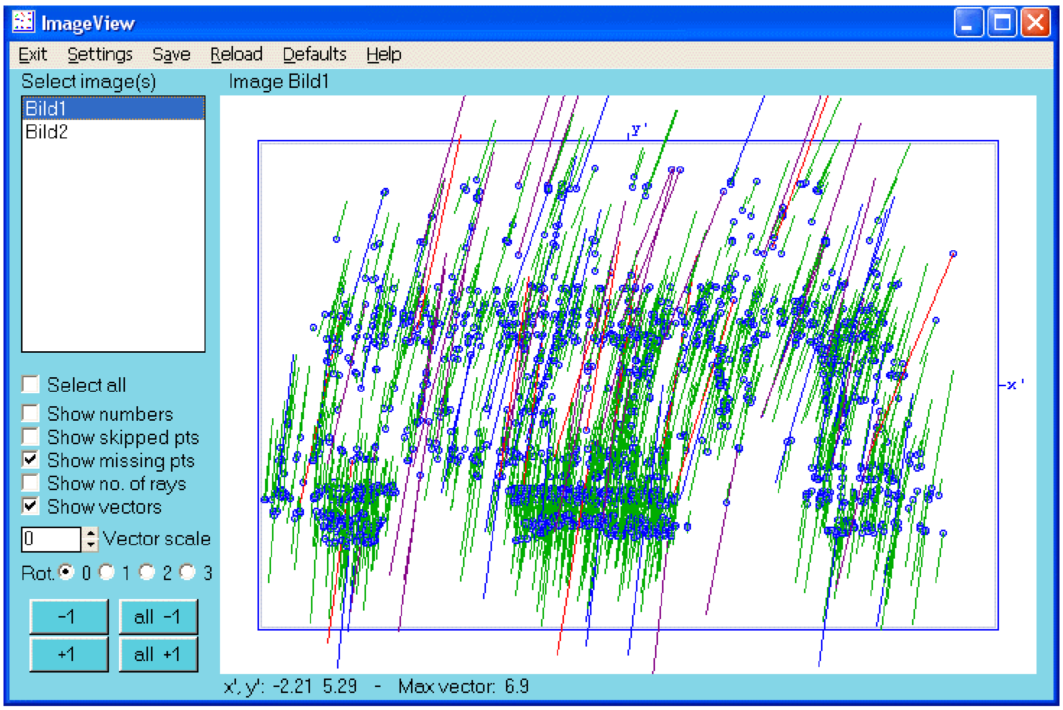

Figure 1. Surprising systematic image residuals.

Figure 1 is the result of an adjustment with moving object points. Figure 2 shows remaining systematic effects in an image stitched from nine single camera heads. Figure 3 shows systematic effects from stitched images from a project, flows with a four single heads camera. Special calibration is required in both cases. Figure 4 shows the summarized point distribution for Figure 3. The systematic effects are high significant.

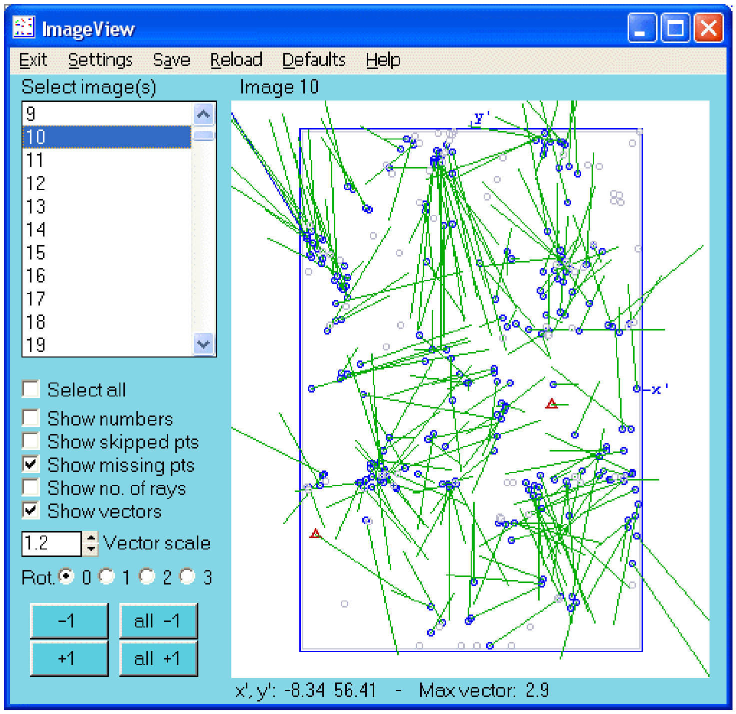

Figure 2. Systematic image residuals from a stitched image.

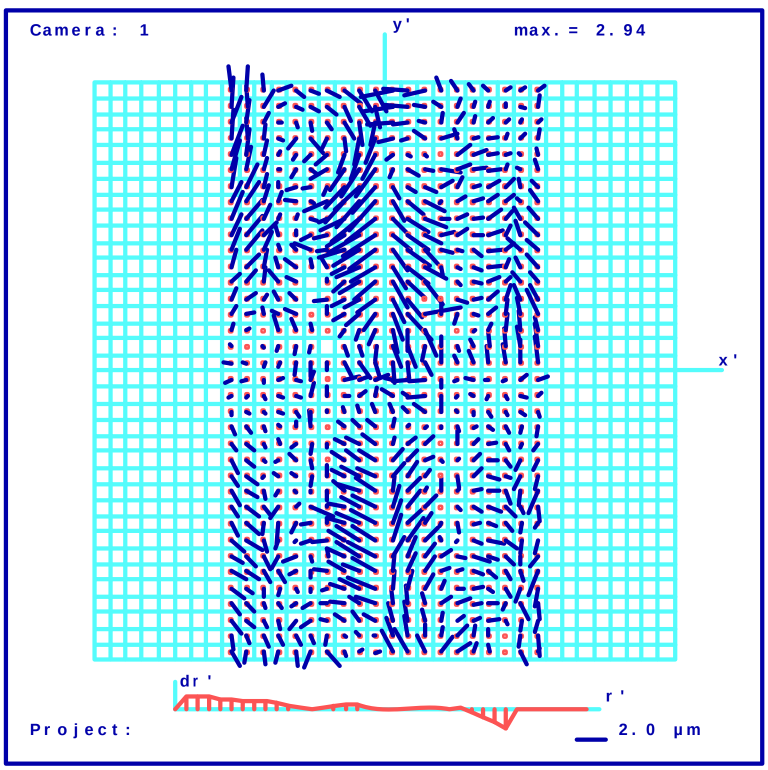

Figure 3. Systematic image residuals in stitched images combined from 1037 photos.

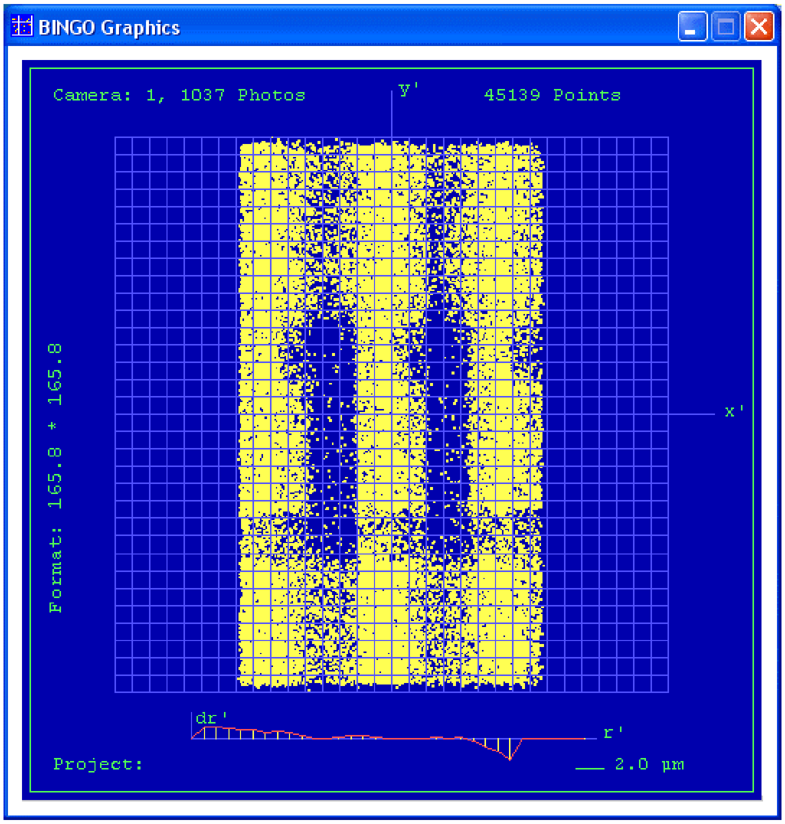

Figure 4. Summarized point distribution from 1037 photos with 45139 photo measurements.

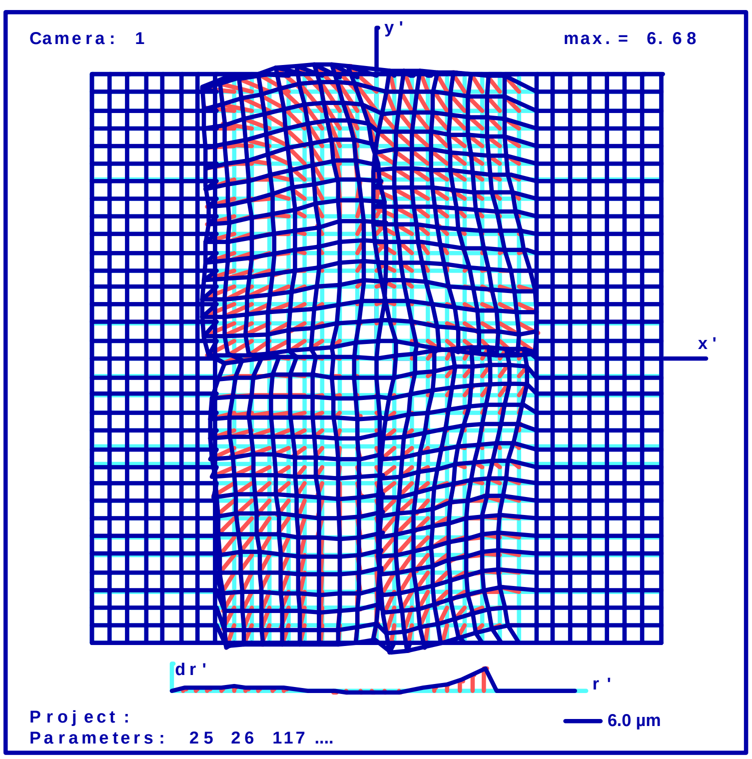

Figure 5. Effects of special self-calibration parameters on the image geometry.

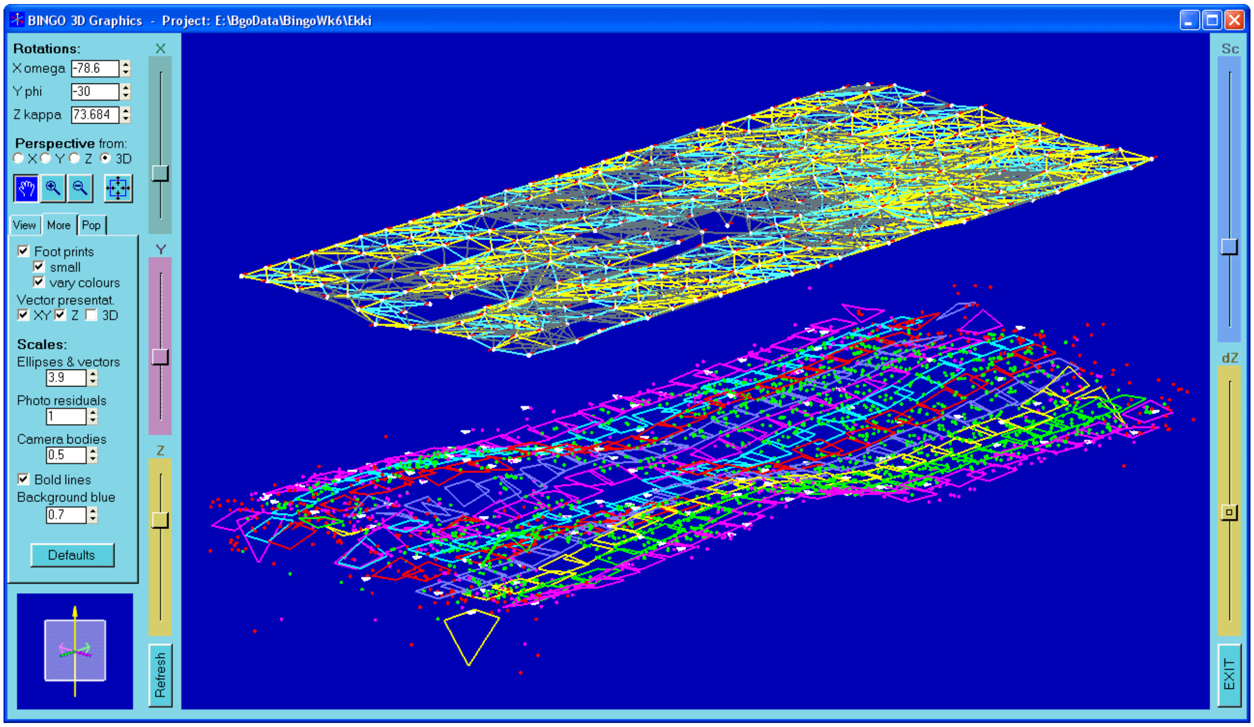

Figure 6. Color coded connections between neighbored photos.
(Footprints have 1/3 of their original size.).

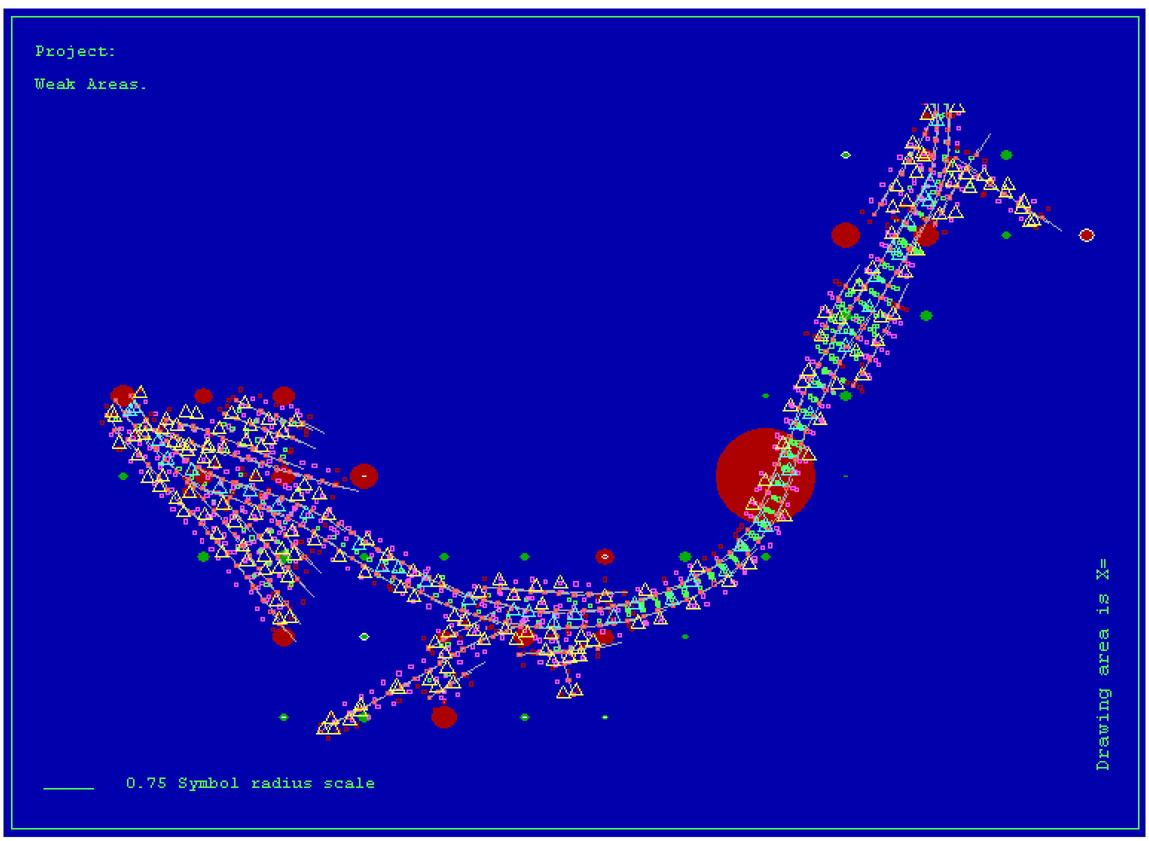

Figure 7. Weak area plotting.
A precision problem occurs in the position of the big red dots.

Figure 6 shows a quite different way to check image measurements form automatic tie-point collection. The color of the lines between the photos is an indication of the number of common points between them. Several images have no connections even though points on the ground have been measured in other images. The block is very weak in those areas.

The green and red dots in Figure 7 indicate the size of the larges confidence ellipsoids in these areas. The user should have a closer look into ranges with very big red dots before the adjustment results will be used for further applications.

Many of the demonstrated effects cannot be recognized without graphical support.

GPS/IMU Data and Their Residuals

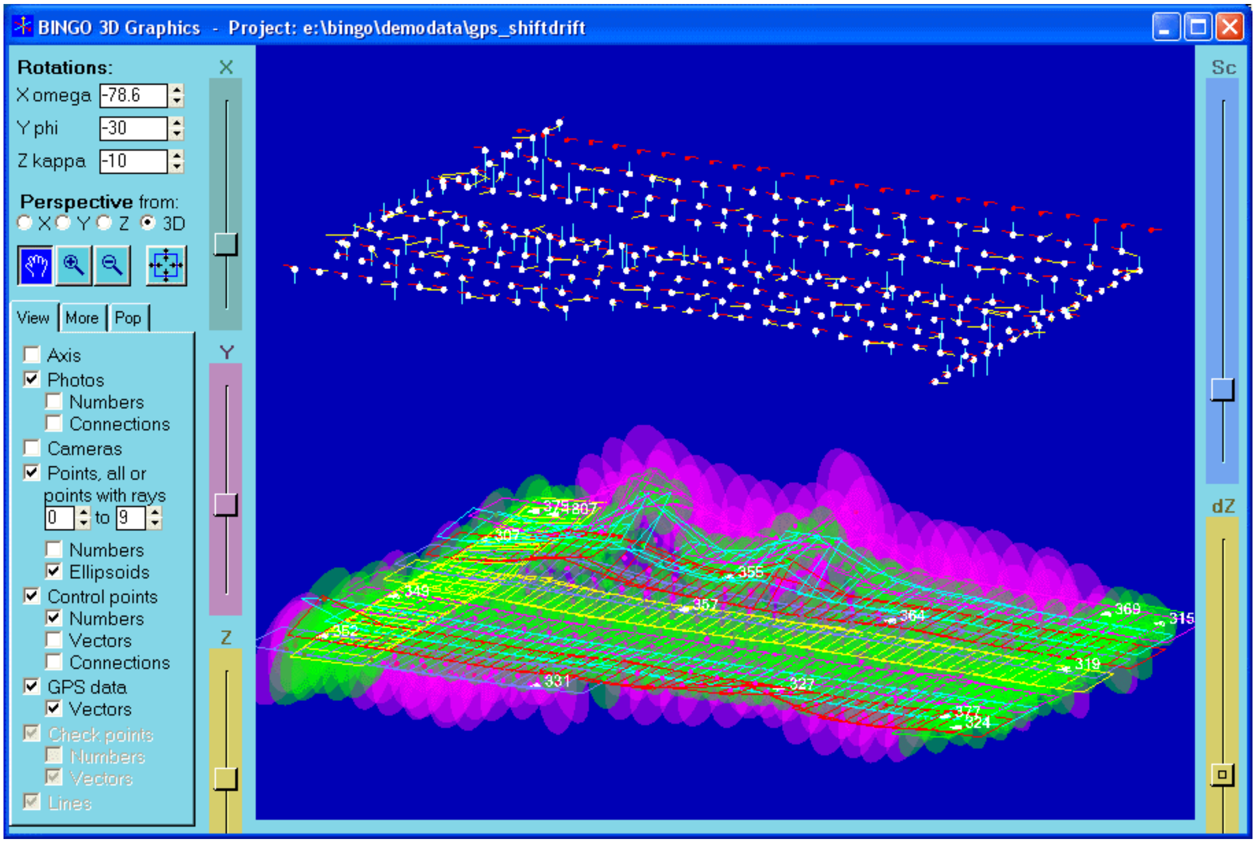

Figure 8. GPS data are missing for the first flight line.
As result we have larger confidence ellipsoids in that region.

GPS residuals can be checked graphically as well in the 3D viewer program. But the sequence in time cannot be recognized. The presentation of IMU residuals in 3D seems to be difficult or not possible. Therefore a presentation of the residuals as a function of time in a diagram can give a lot more of information. Using this graphical presentation, many problems in GPS/IMA data can be identified much easier then in a long list of data.

Figure 9. GPS/IMU residuals from different projects.
Systematic effects and relations between GPS and IMU data can be easily identified.

Ground Control Point Residuals

While photo measurements and GPS/IMU data are the mass data in a photogrammetric block, ground control points are relatively spare. But as well here is the graphical presentation absolutely necessary as demonstrated in figure 10.

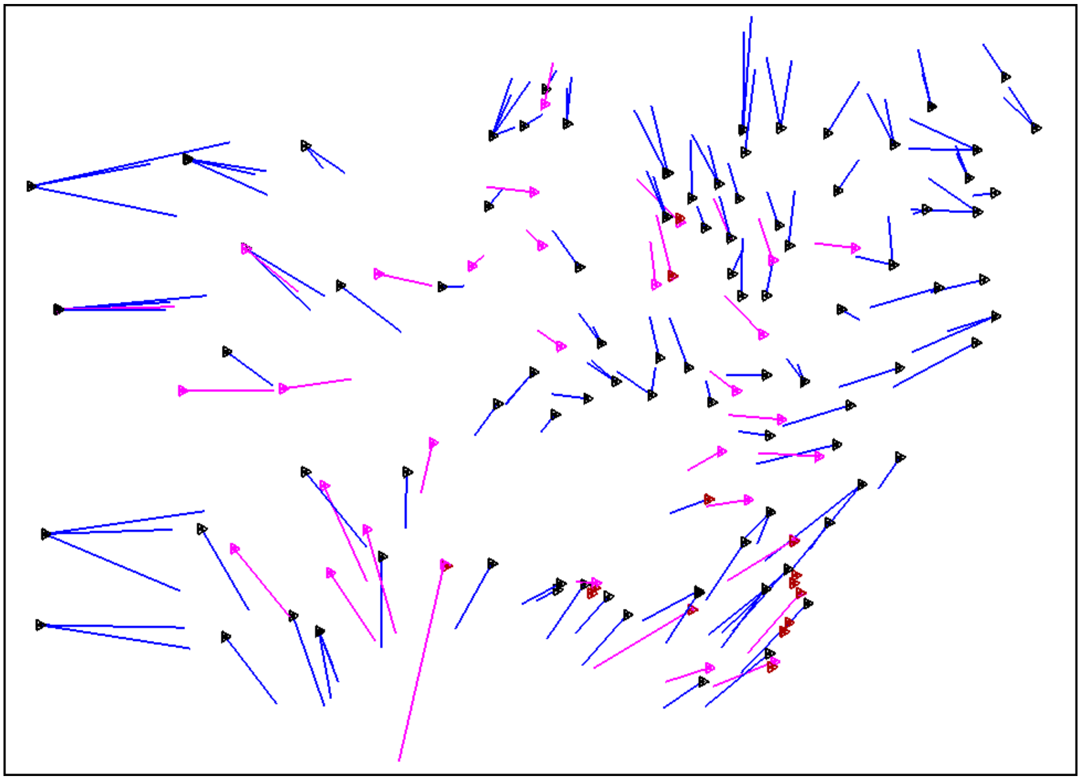

Figure 10. Ground control point residuals showing systematic effects.

The X,Y residuals of the control points (black points, blue vectors) and of the independent check points (pink) are indicating different scales in X and Y and a small share. Two additional parameters, one for different scales in x′ and y′ and another one for share remove this problem completely. Without graphics it would have been very difficult to identify the reason for the big residuals.

CONCLUSIONS AND PROSPECTS

As demonstrated, graphical presentation of bundle block adjustment results is absolutely undeniable, when bigger blocks are processed. But as well the interpretation of the graphics require human interaction and some experience in photogrammetry.

For the future it would be very interesting to use bundle triangulation only as a ″black box″ to fulfill the growing demand of photo geo-referencing for our ″digital earth″. This requires further very intelligent algorithms to replace human eyes and operator's experience by automated processes. This is a very big challenge for the developments in the next decades.

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