Digitization and Rectification of Transparencies with the Analytical Plotter P3

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Abstract

We present a concept and a realization of a program package for the digitization and rectification of transparencies with an extended analytical plotter Planicomp P3. The program should be useful for all domains of digital photogrammetry.

Rectification is possible in four modes: into the image coordinate system, into the epipolar plane (normal system), into a free definable tilted plane in object space, or into an orthophoto, based on a digital terrain model.

The system produces images of any pixel size and treats colour images by sequential digitizing colour separations.

Keywords

Scanner, Digitization, Rectification, Orthophoto.

1 Introduction

We present a concept and a realization of a program package for the digitization and rectification of transparencies with an analytical plotter Planicomp P3.

Sensors yielding digital images are not yet used in topographic applications of photogrammetry, but of course in close range photogrammetry [FRASER/BROWN 86, DOLD/RIECHMANN 91, LUHMANN 91] and in remote sensing [STRATHMANN 90, BÄHR 91]. But scanned analogous images open the door to digital photogrammetry.

There is a wide range of scanners for transparencies on the market [LEBERL 91, EHLERS 91]. Desktop scanning allows very fast scanning (<1'/10 *MByte*) for a low price (≤2000 US$) but with low resolution (300 *dpi* correspond to 80 μm). In contrast the photogrammetric scanners, like the PhotoScan PS1 from Zeiss and Intergraph [FAUST 89], permit the required high accuracy (e. g. 2 μm) combined with a high speed(≤20'/400 *MByte*), but they are comparably expensive. Our system is an alternative as it reaches photogrammetric accuracy (σ=3 μm) with moderate speed (<2^h/100 *MByte*) without high additional costs.

The system is based on a Planicomp P3, extended by two video cameras, which are fixed within the optical path. The geometric precision of our system thus is based on the quality of the analytical plotter, in contrast to other CCD scanners which move the video camera over the analogous image, with the problem of driving precision and mechanic stability [LUHMANN/WESTER-EBBINGHAUS 86].

The image of a video camera can be handeled by a Personal Computer, but for digitizing bigger areas of transparencies scanning has to be done patchwise.

The system is able to digitize and rectify images offline and online in four modes:

- Parallel to the image coordinate system.
  This is useful for all photogrammetric measurements in digital images which take place in the image coordinate system with respect to the (free definable) pixel resolution. This e. g. may be used for aerial triangulation purposes. Another example are interactive plotting systems like the PHIDIAS system [BENNING/EFFKEMANN 91].
- Parallel to an epipolar plane (normal system of a stereo model).
  This is interesting for all correlation software using the epipolar geometry, in particular for automatic production of digital terrain models (DTM), e. g. in combination with MATCH-T [KRZYSTEK 91, KRZYSTEK/WILD 92].
- Parallel to a free definable tilted plane in object space. This mode is useful for rectifying building fronts or other nearly plane objects.
- Rectifying a scanned image to an orthophoto.
  This mode needs a digital terrain model and is the most complex one. It is useful for single orthophotos.

The system is able to produce images of any pixel size and treats colour images by sequentially scanning the images to colour separations with the aid of corresponding filters.

This program package is an efficient tool for scanning parts of images or small transparencies, especially for occasional work of those who use the analytical plotter anyway. Due to the avialability of several modes the system is highly flexible and useful for all domains of digital photogrammetry.

2 System Concept

2.1 Coordinate Systems

Planning a rectification as well as doing the rectification itself needs a number of different geometric transformations. Homogeneous representation of the transformations is common and also used here [e. g. FISCHER 91]. In homogeneous coordinates a transformation is written as a matrix multiplication. Of special interest is the property of the transformation matrices to be connectable by multiplications. The transformation from object space to CCD array system (*sensor*) then needs only one matrix multiplication consisting of the individual transformations from points $\overset{obj}{\boldsymbol{p}}$ in object space to the corresponding points $\overset{ccd}{\boldsymbol{p}}$ in the sensor system:

$$\overset{ccd}{\boldsymbol{p}} = \boldsymbol{T}^{ccd}_{obj} * \overset{obj}{\boldsymbol{p}} = \boldsymbol{T}^{ccd}_{car} * \boldsymbol{T}^{car}_{img} * \boldsymbol{T}^{img}_{obj} * \overset{obj}{\boldsymbol{p}}$$

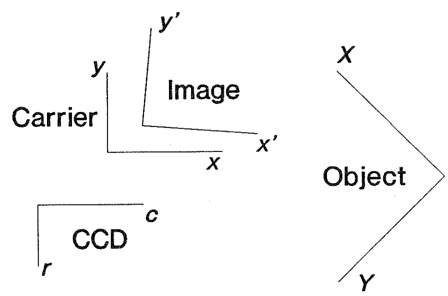


Figure 1: *Coordinate systems.*

The geometric calibration of the sensor with respect to the carrier stage (T^{ccd}_{car}) is part of the scan software. The other transformations are derived from the interior, relative and/or absolute orientation results, thus read from external files and combined to homogeneous transformation matrices. All Zeiss orientation software, PHOCUS, P-CAP, C100, provide a standardized file in a socalled **P**hotogrammetric **O**rientation **D**ata **E**xchange **F**ormat (PHOREX) [SAILE 89]. Therefore the photogrammetric orientation has to be executed before starting this program. Depending on the mode of rectification different orientation data is required.

- Rectifying to the image coordinate system: Only the rectangular or affine transformation parameters from image to carrier stage system are necessary (interior orientation).

- Rectifying to a normal system first the epipolar plane has to be defined as a base line oriented plane with respect to the image system. For building this transformation matrix only the results of the interior and the relative orientation are necessary.

- Rectification to a tilted object plane is a similar case. The object plane is defined by four homologous points in both, object plane and image system, because of eight independent transformation parameters of the projection of planes. The parameters can be calculated directly from an algorithm which uses oblique-angled coordinate axes from diagonals of the four points [RINNER/BURKHARDT 72]. Only the interior orientation is needed, too.

- For orthophoto rectification all the data of interior and exterior orientation is required. In addition terrain height information is necessary. This information is expected to be in the form of a digital terrain model (DTM). We require the DTM nodes to be identically with orthophoto pixel nodes (the pixel size will be adapted to DTM meshes).

The interior orientation of the camera contains distortion values. These parameters are the only part which cannot be handled by homogeneous transformation rigorously. But for the digitizing it is possible to simplify the continous distortion function by a piecewise constant or linear function as the sensor area is a few mm in diameter, and the distortion usually varies for a few μm in cm-intervalls only. Therefore the error of this approximation can be neglected.

2.2 Partitioning the Area of Interest

The object system depends on the rectification mode: it is the image system, a normal system, a plane object system or a threedimensional object system. The object area the user is interested in being digitized and rectified is a free definable *section* in object units. The definition can be given by a polygon, by a centre of a rectangle with length and width, or by a corner of a rectangle with sidelengths. In any case the section is the minimum boundary box around the area of interest. Also free definable is the pixel size respectively the resolution of the rectified image in object units.

The section corners projected to the sensor system form a perspective quadrangle, normally larger than the sensor area. For this reason the section must be divided into *patches* of a constant number of pixel rows and columns, which after projection never exceed the sensor size. Instead of the whole sensor area it is possible to declare a limited central sensor area for exclusive use [WIESEL/BEHR 88].

The question for the optimal patch size is non-trivial. In principle it leads to a nonlinear integer optimization problem. Realized is an approximative iterative algorithm. An initial patch is build in the largest scaled section area. The patch charaterized by m rows and n columns of object pixels is transformed to the sensor system. An enclosing box detects the required sensor area and increments or decrements m and n for the next iteration. The found patch is the largest one in the sensor system. All other patches do not exceed sensor limitations, too.

Result of the partitioning is a description of the section consisting of the origin of the section, the number of patches in rows and columns, and the number of pixels per patch in rows and columns.

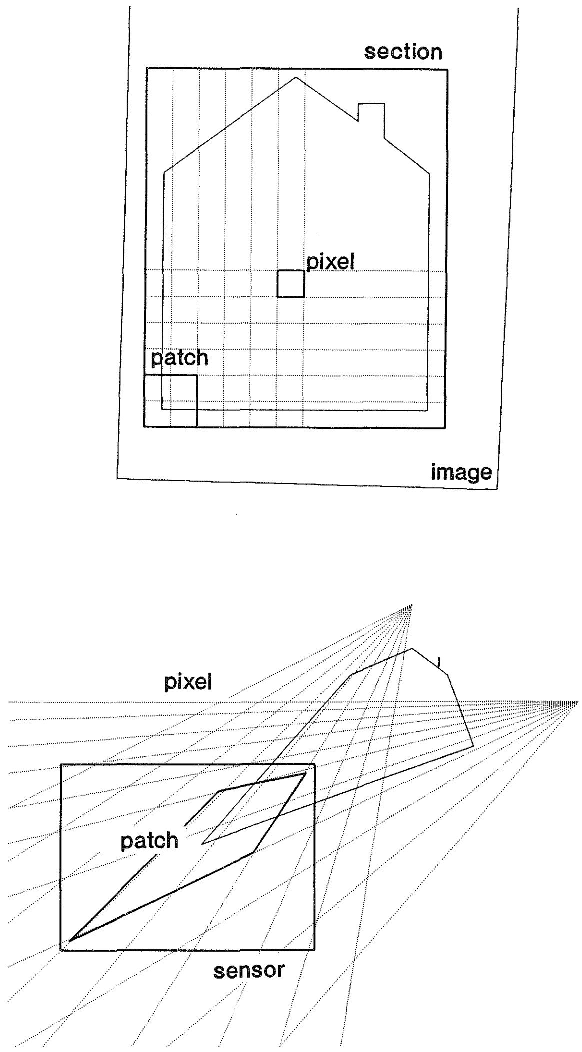


Figure 2: *The upper figure shows the section as the area of interest, with free defined pixels.*
The lower figure shows the determination of the patch size from distorted pixels and sensor area size. The found patch is also tranferred into the object section.

2.3 Properties of Patches

Variable patch scales from perspectivity leads to different enclosing boxes in the sensor system. It saves time and memory in case an individual window size in the digitized image for every patch is used. Only this window should be rectified and stored.

If the patch is transformed not to sensor but to carrier stage system, we can calculate the enclosing box in a similar way. The centre of this box could be the position which the carrier stage must be moved to if the sensor were centered to the actual carrier stage position. In fact a shift must be added. This shift is constant for a calibration period and independent from the actual carrier stage position. Now the centering of the box relative to the sensor is guaranteed.

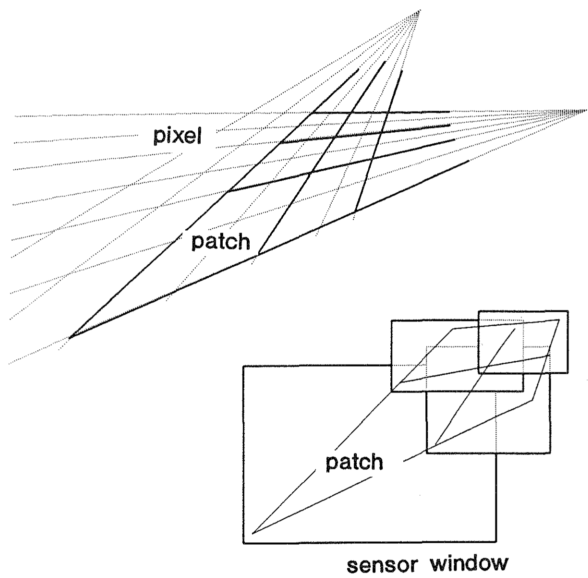


Figure 3: *The sensor window size depends on the distortion of the patch.*

The object system is either plane or at least piecewise plane. For this reason the projective distortion leads to (piecewise) perspective patches. Rectification of a perspective patch to the rectangular one in object system is done indirectly by the projective transformation. Then the gray value is determined in the digitized image by an interpolation method like nearest neighbourhood, bilinear or cubic interpolation [WIESEL 85, JÄHNE 89], which can be chosen by the user.

Instead of applying projective transformation for every pixel per patch it is possible to use anchor points which are transformed projectively. A bilinear interpolation between the anchor points is used to calculate the object pixel position in the digitized image. This is much faster due to the recursive character of the geometry calculation [LEBERL 75, BEHR/LUTZ 89, BEHR 89].

Approximating the projective transformation by bilinear interpolation causes errors. This error reveils when determining the centre of a quadrangle: the bilinear centre is obtained by intersecting the connections of the midpoints of nonneighbouring edges, while the perspective centre is the intersection of the diagonals.

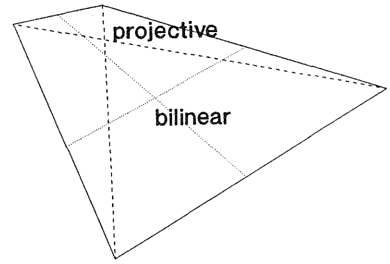


Figure 4: *Example of different results from bilinear interpolation and projective transformation.*

That is why the patches are to be divided into *meshes* of sufficient parallel edges.

2.4 Use of Image Pyramids

Part of the rectification is a reduction or an enlargement of the digitized pixel to the rectified pixel. This may lead to a loss of quality of the digital data. Reductions may cause aliasing effects, and enlargements may lead to saw-toothed ramps [HABERÄCKER 89].

To prevent or at least to reduce these effects it would be ideal to have pixel proportions of 1:1 between digitized and rectified image. But the sensor pixel size is fixed, and the resolution of the rectified image is chosen by other criteria.

We have two different means to counteract. First we may choose a higher interpolation method. This is only recommendable (and automatically chosen by the program) in case of enlargements. Second, we may use image pyramids. An image pyramid contains the digitized image in different levels of resolution. It is built by picking every second pixel from the next lower level after smoothing this level. The pyramid is more information preserving than the interpolation method and leads to better quality [JÄHNE 89]. The additional memory for the pyramid is only a third of the digitized image.

In this multiresolutional image it is possible to look for a pyramid level near the proportion factor 1 with respect to the rectified image. This pyramid level will be used for the rectification. For use in differential rectification the pyramid level determination includes a smoothing algorithm to suppress flickering in levels.

2.5 Calibration

Calibration of the scanning system consists of the geometric and the radiometric part. The geometric calibration leads to the orientation of the sensor relative to the carrier stage system. This job has to be done before preparing the scan process, and is to be repeated from time to time. The radiometric calibration is a correction of brightness and contrast of every digitized image. This takes place during the scan process continously.

2.5.1 Geometric Calibration

Assuming both systems as plane and the planes as parallel, the aim of the geometric calibration is to determine the homogeneous tranformation matrix which represents an affine transformation from the carrier stage system to the sensor system.

If we name the variables:

x_j, y_j	any image point in carrier stage coordinates
x_M, y_M	actual carrier stage position
r_M, c_M	sensor location of carrier stage position
r_j, c_j	sensor location of image point

the elements of following transformation matrix are to be determined:

$$\begin{pmatrix} 1 \\ x_j - x_M \\ y_j - y_M \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e & f \\ 0 & h & i \end{pmatrix} * \begin{pmatrix} 1 \\ r_j - r_M \\ c_j - c_M \end{pmatrix}$$

and if (r_M, c_M) is assumed to be constant:

$$\begin{aligned} \begin{pmatrix} 1 \\ x_j - x_M \\ y_j - y_M \end{pmatrix} &= \begin{pmatrix} 1 & 0 & 0 \\ (-e * r_M - f * c_M) & e & f \\ (-h * r_M - i * c_M) & h & i \end{pmatrix} * \begin{pmatrix} 1 \\ r_j \\ c_j \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 & 0 \\ d & e & f \\ g & h & i \end{pmatrix} * \begin{pmatrix} 1 \\ r_j \\ c_j \end{pmatrix} \end{aligned}$$

We have to consider the movement of the carrier stage to be a variable shift, and the excentric position of the sensor to the measurement mark respectively to the actual carrier stage position as a constant shift.

The P3 optics doesn't project the measuring mark to the sensor. Nevertheless we use the mark as a reference to the P3 coordinates, and a fiducial (or any other suitable target) for the transfer to the sensor. The fiducial as a synthetic pattern is easy to be measured automatically, e. g. by cross correlation [FÖRSTNER 92]. Centering the fiducial to the measuring mark leads to the shift parameters, and moving the fiducial gridwise over the sensor these observations lead to the affine parameters. The module enables a nearly full automation of the interior orientation.

2.5.2 Radiometric Calibration

The radiometric calibration is necessary to suppress visible brightness differences within the patches and from patch to patch. The properties of the sensor have to be modeled in combination with the illumination of the plotter. The illumination of an analytical plotter may show a fall-off of the intensity [GÜLCH 86, WIESEL/BEHR 88, BEHR 89]. Because the bulb is not centered in the optical path, this effect in general is not symmetrical, and it is depending on actual voltage and age of the bulb. Modelling this effects is too complex, which is the reason why the constancy of the illumination has to be guaranteed by the hardware as far as possible.

The implemented radiometric calibration is only an adjustment between neighbouring patches. Corrections are calculated from overlapping stripes of two additional digitized rows/columns of pixels per patch. The gray value differences in this stripe are used for the determination of offset and gain. They are used to bilinearly interpolate the radiometric corrections within the patch.

3 System Description

3.1 Hardware

The hardware configuration consists of:

- Analytical plotter Planicomp P3 from Carl Zeiss [SAILE 87];
- Two black and white video cameras with a resolution of 512×768 pixels (Sony, CCIR);
- Two filter wheels with step motors and an interface board;
- Three black and white monitors (Hantarex);
- Frame grabber board ITI VFG-100 with a capacity of 1024×1024×12 *bits*. Only a depth of 8 *bits* is used. (Imaging Technology, compatible to ITI VS-100 and ITI FG-100) [IMAGING 90];
- PC-386 with a mathematical coprocessor.

Two monitors continously show the left and the right video image, and the third one is used to show the actual content of the frame memory. The PC's monitor is be used for the dialog with the user.

The CCD chip of the video cameras contains 512 rows and 768 columns of pixels. The square pixels have an size of about 11 μm in both directions. The sensor area in image plane therefore is about 5.5 mm by 8 mm.

The use of the two carrier stages is only possible sequentially, limited not by the plotter but by the image processing on the PC. The filter wheels allow to digitize red, green and blue colour separations, or to use no filter. The selection is controlled by the software.

The frame grabber converts the analogous video signal into a digital one and puts it into the frame memory [IMAGING 90, JÄHNE 89]. Grabbed images (or defined windows of the images) are put into main memory or into files on the disk. The output of digitizing and of rectification is also written to the disk, using the ITEX binary image format, which can be read by several plotting systems, for example by the Zeiss PHODIS software.

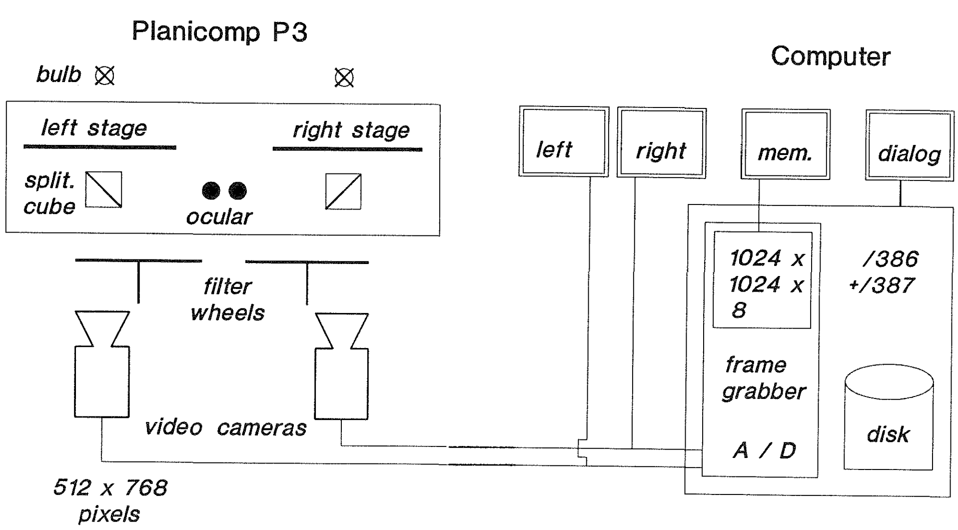
3.2 Preparation

Preparing a scanning job consists of collecting input data, checking their consistency, looking for scan parameters and planning the scan process. Based on the user requirements the following steps are performed:

- combination of the orientation data to yield the necessary transformation matrices,
- partitioning of the scan area into single patches to be digitized,
- and patchwise:
  - calculation of the sensor window size,
  - calculation of the carrier stage moving position,
  - division into meshes,
  - choice of the best fitting image pyramid level.

Result of the preparation is a detailed description of every patch in an internal exchange file.

Figure 5: *Hardware configuration.*



3.3 Processing Steps

Processing is started in one of three modes:

- Offline digitization. Only the digitization takes place. The digitized images are stored for a later processment.
- Offline rectification. Digitized images are expected on disk from an earlier offline digitization.
- Online digitization and rectification. The planned patches are digitized and rectified.

The process of digitizing and rectifying consists of the following steps:

- Initializing the hardware (P3, frame grabber, filter wheels).
- Initializing the cycle of periodical geometric calibrations.
- Loop for all patches:
  - driving the carrier stage to the calculated position,
  - digitizing the window containing the patch,
  - correcting the radiometry of the patch,
  - building the image pyramid,
  - rectifying the patch,
  - storing the rectified patch as an image file.

Most of the described algorithms are selectable under alternatives, and the scan process will differ from the schedule above depending on the user requirements.

Result of the processing is a set of digitized and rectified patches in seperated files, which, when combined, will fill the whole section.

4 First Experiences

The program package is implemented with full functionality for digitizing and rectifying in all the four modes. But real experiences with complete projects are just outstanding.

Time requirements are tested for single passages of the processing (all times in *seconds*):

image size in pixels	reading	image pyramid	anchor points	bilinear interpol.	storing
220×310	0.9	0.4	0.1	8.6	5.0

We can use this information for extrapolating the needed time for rectification of:

- a stereo model area of 10 $cm * 20$ cm with a resolution of 30 μm. The image size would be about 3300∗6700 pixels, that is 325 times as big as the example above. Processing time will be approximately $1^h20'$.
- an orthophoto from a transparency of 23 $cm * 23$ cm with a resolution of 30 μm. The image size would be about 7670∗7670 pixels, that is 862 times as big as the example above. Processing time will be approximately $3^h30'$.

Further experiments will allow more detailed statements.

Real increasing efficiency can be expected from faster processor hardware. Some proposals are the use of transputers [ALBERTZ ET AL. 91] or the transfer to a powerful workstation.

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