DBAT — The Damped Bundle Adjustment Toolbox for Matlab

v0.6.1.0

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Contents

1 Introduction

1.1 Purpose

This purpose of the Damped Bundle Adjustment toolbox is to be a high-level toolbox for photogrammetry in general and bundle adjustment in particular. It is the hope of the authors that the high-level nature of the code will inspire algorithm development. The code is written in Matlab and is verified to work with Matlab version 8.6 (release R2015b). The intention is that at least the computation routines will be Octave-compatible. This has however not been tested yet.

1.2 Contents

1.2.1 Code

The toolbox currently includes routines for (Matlab function names within parentheses):

- File handling:
  - Reading PhotoModeler-style text export files (`loadpm`), and 2D/3D point table exports files (`loadpm2dtbl` and `loadpm3dtbl`, respectively).
  - Reading PhotoScan native (.psz) files (`loadpsz`).
  - Writing PhotoModeler-style text result files (`bundle_result_file`).
- Post-processing:
  - Post-processing of PhotoScan projects (`ps_postproc`). Includes object point filtering on low ray count and low intersection angles.
- Photogrammetric calculations, including:
  - Spatial resection (`resect`).
  - Forward intersection (`forwintersect`).
  - Relative orientation based on the Nistér 5-point algorithm (Stewénius et al., 2006) will be added in the future.
- Bundle adjustment
  - Bundle adjustment proper (`bundle`) using either Classical, Gauss-Newton-Armijo, Levenberg-Marquardt, or Levenberg-Marquardt-Powell damping schemes (Börlin and Grussenmeyer, 2013a, 2014, 2016).
  - Covariance calculations (`bundle_cov`) from the bundle result.
- Various plotting functions, including:
  - Plot image covered by measurements (`plotcoverage`).
  - Plot camera network (`plotnetwork`), either static (as-loaded) or as an illustration of the bundle iterations.

  - Plot of the iteration trace of parameters estimated by bundle (`plotparams`).
  - Plots of quality statistics from the bundle result (`plotimagestats`, `plotopstats`).

- Demo functions using the above functions. The demo functions are detailed in Section 3.1. The available demos are listed by executing the command `help dbatdemos`.

This manual does not contain detailed information about how to use each function. More information may be found by typing `help <function name>` at the Matlab prompt, studying the source code of the demo functions, and reading the source code of each file directly.

1.2.2 Data

The toolbox contains several datasets, including datasets for the Börlin and Grussenmeyer (2016) paper.

- PhotoModeler export files or PhotoScan projects.
- Images. To reduce the size of the distribution package, only low resolution images are included in the package. The corresponding high resolution images can be downloaded from `http://www.cs.umu.se/~niclas/dbat_images`. Further instructions are found in `README.txt` files in the respective image directories.

The simplest way to access the data sets is through the demos, described in Section 3.1.

1.3 Legal

The licence detail are described in the `LICENSE.txt` file included in the distribution. In summary:

- You use the code at your own risk.
- You may use the code for any purpose, including commercial, as long as you give due credit. Specifically, if you use the code, or derivatives thereof, for scientific publications, you should refer to on or more of the papers Börlin and Grussenmeyer (2013a,b, 2014, 2016) that the code is based on.
- You may modify and redistribute the code as long as the licensing details are also redistributed.

2 Installation

```
# == INSTALLATION ==
#
# 1) Download the package file dbat-x.y.z.zip or dbat-x.y.z.tar.gz
#    from https://github.com/niclasborlin/dbat/
#
# 2) Unpack the file into a directory, e.g. c:\dbat or ~/dbat.
#
# 3) Start Matlab. Inside Matlab, do the following initialization:
# 3.1) cd c:\dbat % (change to where you unpacked the files)
# 3.2) dbatSetup  % will set the necessary paths, etc.
#
# 4) To test the demos, do 'help dbatdemos' or consult the manual.
#
#
# ==== Download high-resolution images ====
#
# To reduce the size of the repository and hence download times, only
# low-resolution images are included in the repository. High-resolution
# images can be downloaded from http://www.cs.umu.se/~niclas/dbat_images/.
# For further details, consult the README.txt files in the respective
# image directories.
#
#
```

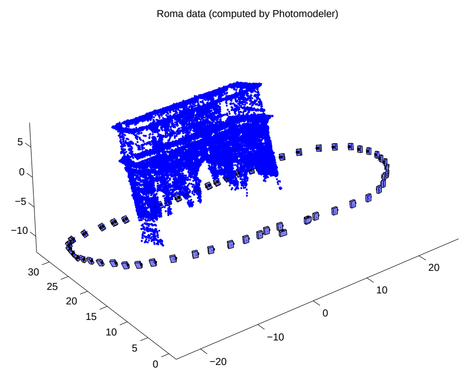


Figure 1: The figure generated by the `loadplotdemo` demo.

3 Usage

3.1 Demos

Hint: You may wish to use the command `close all` between the demos to close all windows.

3.1.1 Plotting

The `loadplotdemo` function load and plots the content of a PhotoModeler text export file. Two examples are included in the toolbox: ROMA and CAM.

ROMA `loadplotdemo('roma')` loads a modified PhotoModeler text export file of the 60-camera, 26000-point project used in Börlin and Grussenmeyer (2013a). The camera network, as computed by PhotoModeler, is plotted with camera 1 aligned to the cardinal axes. The result should look like Figure 1. The figure is a standard Matlab 3D figure and may e.g. be rotated or zoomed using the camera toolbar.

CAM `loadplotdemo('cam')` demo loads a modified PhotoModeler text export file of a 21-camera, 100-point camera calibration project. The camera network, as computed by PhotoModeler, is plotted and should look like Figure 2. The figure is a standard Matlab 3D figure and may e.g. be rotated or zoomed using the camera toolbar.

3.1.2 Camera calibration

The `camcaldemo` demo loads the camera calibration export file from Section 3.1.1 and runs a camera calibration. The EXIF focal length is used as the initial value. The other values are set to "default" values, e.g. the principal point at the center of the sensor and all lens distortion parameters equal to zero. The initial value for the EO parameters are computed by spatial resection (Haralick et al., 1994; McGlone et al.,

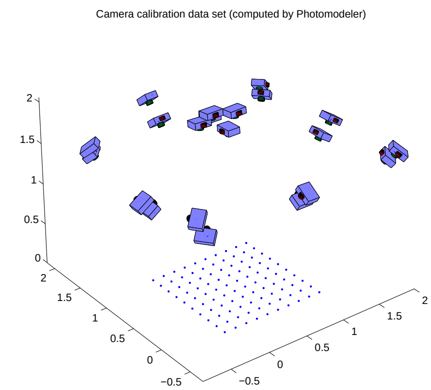


Figure 2: The figure generated by the `loadplotdemo2` demo.

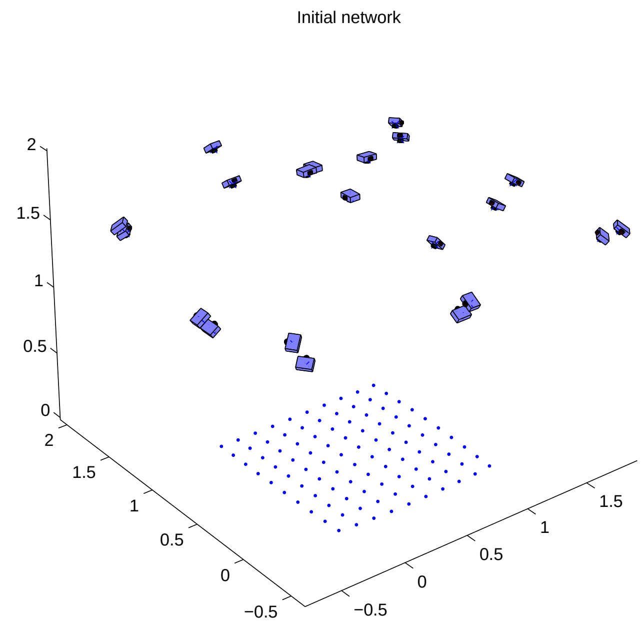
2004, Chap. 11.1.3.4) using the control points defined for the PhotoModeler calibration sheet. The initial OP coordinates are subsequently computed by forward intersection.

The bundle adjustment is run with Gauss-Newton-Armijo damping (Börlin and Grussenmeyer, 2013a). The result is given in a number of plot windows and a Photomodeler-style result text file. The result plots are of two kinds: Plots that show the evolution of the iterations and plots that show the quality of the input or output data. The former plots may be useful to understand how the bundle adjustment works but also to "debug" a difficult network that has convergence difficulties. The latter plots give information about the quality of the result and may also provide clues on how to improve a network when the bundle did converge.

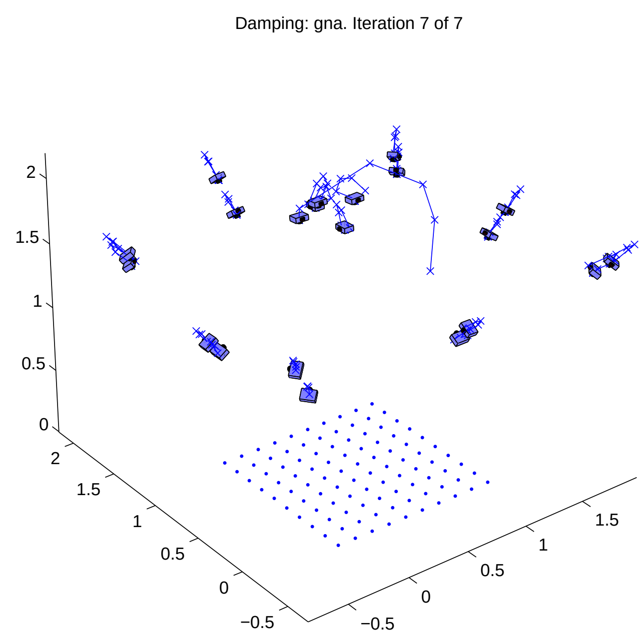
Evolution plots The evolution plots are collected in figures 3–7. Figure 3 shows a snapshot of the 3D trace figure at the beginning and end of the iterations. As default, the evolution is presented iteration by iteration with intervening presses of the return key. The figure window is interactive and may be rotated, zoomed, etc. In this example, it is clear in Figure 3b that one camera station had poorer initial values than the rest.

Figures 4–6 contain three plots showing the evolution of the internal orientation (IO), external orientation (EO), and object point (OP), respectively, during the iterations. The IO plot is split into a focal/principal point panel and a radial and tangential distortion panel, where the radial distortion parameters are scaled to provide more information. The EO plot contains a camera center panel and an ω-ϕ-κ Euler angle panel. The EO and OP plots are interactive. Lines in the plots or legends may be selected and all corresponding lines will be highlighted. In the top panel of Figure 5, the motion of one camera stands out. Clicking that line reveals that it belongs to camera station 21, which can be further investigated to decide if it should be excluded from the calibration.

The final evolution plot, shown in Figure 7, illustrates the evolution of the norm of the total residual and the damping behaviour, if any, during the bundle iterations. In this example, the Gauss-Newton-Armijo linesearch damping is active during the first two iterations. For further details on the damping, see Börlin and Grussenmeyer (2013a).



(a) Initial network configuration.



(b) Network configuration after convergence, with camera center trace lines.

Figure 3: 3D network evolution during the iterations. Only the EO and OP parameters are illustrated. In this example, the variation of the OP coordinates is barely visible.

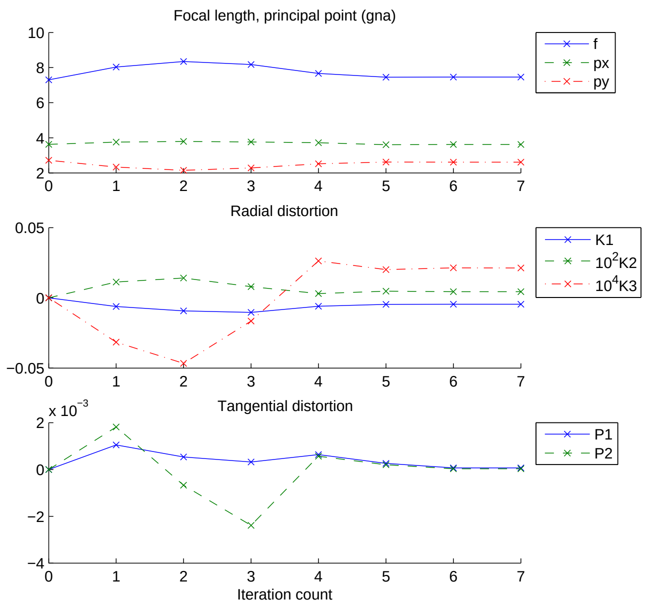


Figure 4: Evolution of IO parameters during the iteration sequence.

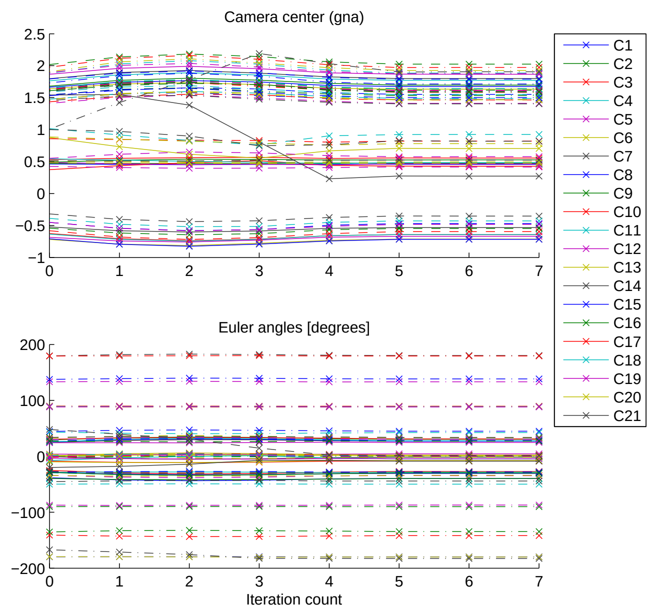


Figure 5: Evolution of EO parameters during the iteration sequence.

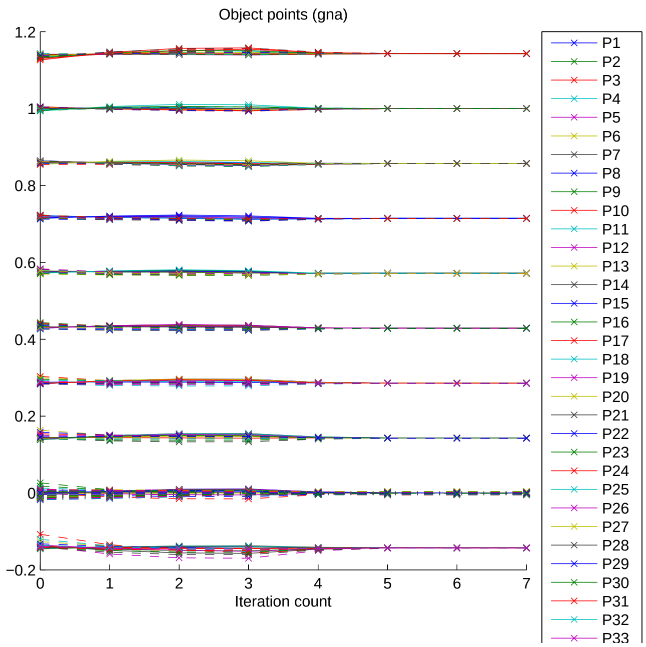


Figure 6: Evolution of OP coordinates during the iteration sequence.

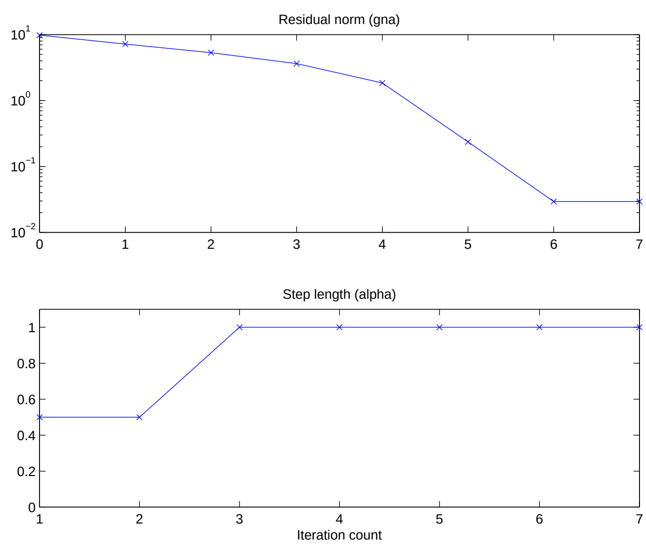


Figure 7: Residual evolution and damping behaviour during the iterations.

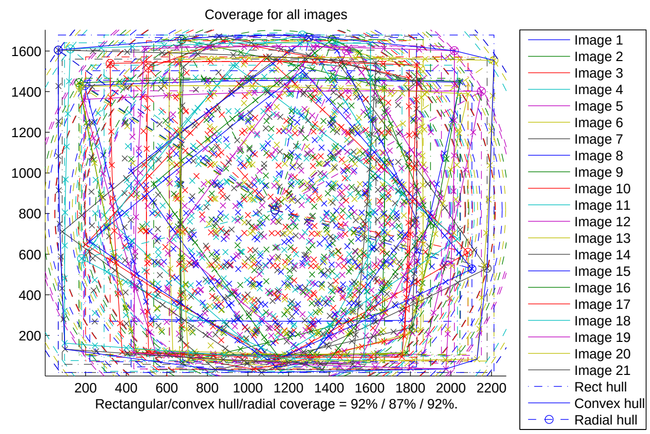


Figure 8: Plots of input/output statistics: Image coverage.

Quality plots The quality plots a gathered in figures 8–10. Per-image quality statistics is shown in Figure 9. The statistics presented for each image are the image coverage (rectangular coverage, convex hull coverage, and radial coverage); the number of measured points; the average (RMS) point residual; and the standard deviations for the EO parameters for the camera stations. In this example, the data does not give any obvious support to exclude the suspected image 21 from the calibration.

The image coverage is detailed in a separate Figure 8. The plotted data is selectable. All observations from a specific image, including their convex hull, will be highlighted when a point or line is selected.

Finally, the per-OP quality statistics in Figure 10 show the number of observations per OP; the maximum ray intersection angle; the average (RMS) point residual; and the OP coordinate standard deviation. The presentation may be zoomed to show only a subset of the OPs by activating the "zoom" function of the figure window.

Result file The result file is modelled after the PhotoModeler result file. The result file is listed in Appendix A.3.

3.1.3 Bundle adjustment

ROMA The `romabundledemo` function loads the project from Section 3.1.1 and present essentially the same plots and the `camcaldemo`. This demo uses the PhotoModeler file as input to the bundle adjustment that runs a few iterations until convergence. The same result file and result plots as `camcaldemo` are essentially generated. Since the project is larger (60 cams/26 000 points) than the previous example (20 cams/100 points), the computation will take a bit longer. Computation time was around one minute running on a HP compaq dc7800 with an Intel Core2 Quad CPU Q9300 @ 2.50GHz under 64-bit Ubuntu 12.04 (kernel 3.5.0-45).

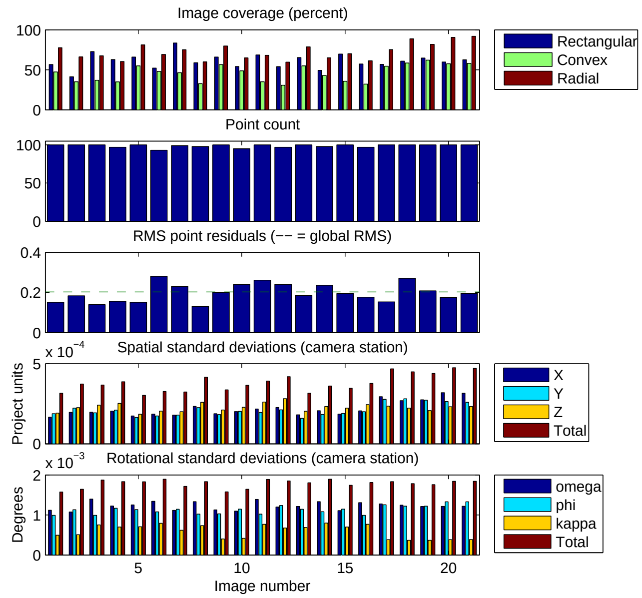


Figure 9: Plots of input/output statistics: Image statistics.

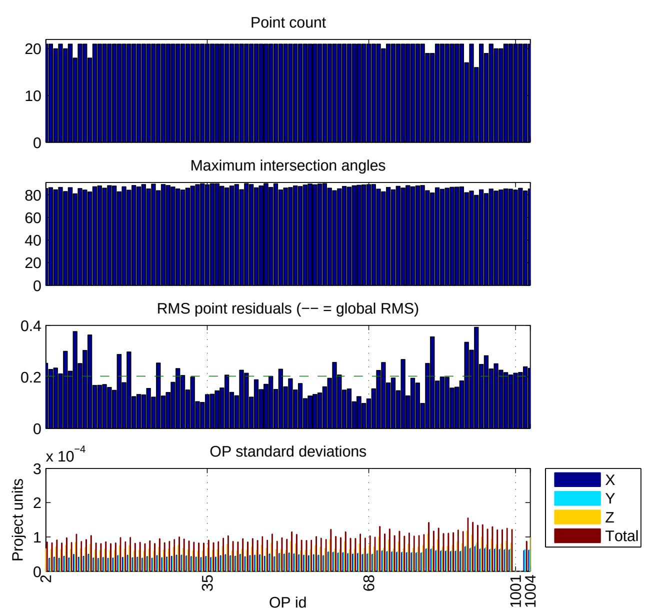


Figure 10: Plots of input/output statistics: Object point statistics.

PRAGUE'16 The `prague2016_pm` function displays six projects that compare the result of the bundle adjustment procedure in DBAT and the results of PhotoModeler (Börlin and Grussenmeyer, 2016). Similarily, the `prague2016_ps` function displays the results of a comparison between DBAT and PhotoScan.

The v0.5.1.6 release includes a fix to a bug the distributed the image observation weights incorrectly. The result is slightly different estimation results than in Börlin and Grussenmeyer (2016). However, the conclusions remain valid.

3.2 Using your own data

This section describes how to import you own data using PhotoModeler text export files. If you have another type of input file, you may be able to write your own loader. Otherwise, if you have a text file you wish to import, feel free to mail the file to the the toolbox authors and request an import function. Althought we cannot guarantee anything, we may adhere to the request, time permitting.

3.2.1 Export from PhotoModeler

To import a PhotoModeler project into the toolbox, the following steps are valid in PhotoModeler Scanner 2012:

1. Export the project using the *Export Text File* menu command. If the command is not available, follow the instructions in Appendix A.1.

2. After export, open the *Project/Cameras...* dialog and select the camera that was used in your project.

3. Open the generated text file in a text editor.

   (a) On the 2nd line (usually reading `0.00005 20`), append the width and height in pixels of your images, e.g. to `0.000500 20 5616 3744`.

   (b) Inspect the 4th line. For instance, the original data in `roma.txt` was (some trailing zeros removed):

   `24.3581 18.1143 12.0 35.96404 24.0 0.00022 -0.0 0.0 0.0 0.0`

   The values correspond to the following camera parameters:

   `focal pp_x pp_y format_w format_h K1 K2 K3 P1 P2`.

   Notice that most of the significant digits of K1–K3 were lost in the text export.

   (c) Update the parameter values on the 4th line with values from the camera dialog *for each parameter with a larger number of significant digits in the dialog*. This usually means all parameters except `format_w`. In the `roma.txt` test case, the 4th line was modified to:

   `24.3581 18.1143 12 35.96404 24 2.174e-4 -1.518e-7 0 0 0`.

3.2.2 Loading into Matlab

1. In Matlab, run step 2 from Section 2 if not already done.
2. Call `loadplotdemo` with the name of your text export file as first parameter. A figure with your camera network, aligned with the first camera and rotated to have +Z 'up', should now have been generated.

3.2.3 Using the bundle adjustment of DBAT

Modify either of the demo functions to match what you want to do. If you run into any problems, send us an email. The interesting results may either be in the plots or in the result file.

References

N. Börlin and P. Grussenmeyer. Bundle adjustment with and without damping. *Photogrammetric Record*, 28(144):396–415, Dec. 2013a. doi: 10.1111/phor.12037.

N. Börlin and P. Grussenmeyer. Experiments with metadata-derived initial values and linesearch bundle adjustment in architectural photogrammetry. *ISPRS Annals of the Photogrammetry, Remote Sensing, and Spatial Information Sciences*, II-5/W1:43–48, Sept. 2013b.

N. Börlin and P. Grussenmeyer. Camera calibration using the damped bundle adjustment toolbox. *ISPRS Annals of the Photogrammetry, Remote Sensing, and Spatial Information Sciences*, II(5):89–96, June 2014.

N. Börlin and P. Grussenmeyer. External verification of the bundle adjustment in photogrammetric software using the damped bundle adjustment toolbox. *International Archives of Photogrammetry, Remote Sensing, and Spatial Information Sciences*, XLI-B5:7–14, July 2016.

D. C. Brown. Close-range camera calibration. *Photogrammetric Engineering*, 37(8): 855–866, 1971.

R. M. Haralick, C.-N. Lee, K. Ottenberg, and M. Nölle. Review and analysis of solutions of the three point perspective pose estimation problem. *Int J Comp Vis*, 13(3): 331–356, 1994.

C. McGlone, E. Mikhail, and J. Bethel, editors. *Manual of Photogrammetry*. ASPRS, 5th edition, July 2004. ISBN 1-57083-071-1.

H. Stewénius, C. Engels, and D. Nistér. Recent developments on direct relative orientation. *ISPRS J Photogramm*, 60(4):284–294, June 2006.

A Appendices

A.1 Enabling text export from PhotoModeler

.

Some versions of PhotoModeler do not have the text file export option enabled by default. In that case, the following steps worked in PhotoModeler Scanner 2012:

1. Right-click on the main window toolbar, select *Customize toolbar...*.
2. In the *Commands* tab, select the *File* category.
3. Drag the *Export Text File...* command to a toolbar of your choice.
4. Now you should be able to export your project as a text file by clicking on the *Export Text File* button.

A.2 Camera model

Currently, the only supported camera model is the omega-phi-kappa Euler angle camera model (McGlone et al., 2004, Ch. 2.1.2.3) with the Brown (1971) lens distortion model.

A.3 Result file example

```
Damped Bundle Adjustment Toolbox result file
   Project Name: Bundle Soln PhotoModeler Calibration Project
   Problems and suggestions:
      Project Problems: Not evaluated
      Problems related to the processing: (1)
         One or more of the camera parameter has a high correlation (see below).
   Information from last bundle
      Last Bundle Run: 15-Dec-2016 10:36:58
      DBAT version:    0.6.1.0 (2016-12-15)
      Status:          OK (0)
      Sigma0:          1.68901
      Sigma0 (pixels): 0.168901
      Processing options:
         Orientation:             on
         Global optimization:     on
         Calibration:             on
         Constraints:             off
         Maximum # of iterations: 20
         Convergence tolerance:   1e-06
         Singular test:           off
         Chirality veto:          off
         Damping:                 gna
         Camera unit (cu):        mm
         Object space unit (ou):  m
         Initial value comment:   Camera calibration from EXIF value
      Total error:
         Number of stages:     1
         Number of iterations: 9
         First error:          30884.2
         Last error:           103.099
      Precisions / Standard Deviations:
         Camera Calibration Standard Deviations:
            Camera1 (camera unit cu=mm)
               Focal Length:
```

```
            Value:        7.45894 cu
            Deviation:    0.00109 cu
       Xp - principal point x:
            Value:        3.61664 cu
            Deviation:    0.000858 cu
       Yp - principal point y:
            Value:        2.60896 cu
            Deviation:    0.000988 cu
       Fw - format width:
            Value:        7.25319 cu
       Fh - format height:
            Value:        5.43764 cu
       K1 - radial distortion 1:
            Value:        0.00457026 cu^(-3)
            Deviation:    2.31e-05 cu^(-3)
            Significance: p=1.00
       K2 - radial distortion 2:
            Value:        -4.25869e-05 cu^(-5)
            Deviation:    2.76e-06 cu^(-5)
            Significance: p=1.00
            Correlations over 95%: K3:-97.9%.
       K3 - radial distortion 3:
            Value:        -2.15843e-06 cu^(-7)
            Deviation:    1.05e-07 cu^(-7)
            Significance: p=1.00
            Correlations over 95%: K2:-97.9%.
       P1 - decentering distortion 1:
            Value:        -6.5657e-05 cu^(-3)
            Deviation:    3.67e-06 cu^(-3)
            Significance: p=1.00
       P2 - decentering distortion 2:
            Value:        -2.9636e-05 cu^(-3)
            Deviation:    4.05e-06 cu^(-3)
            Significance: p=1.00
       Iw - image width:
            Value:        2272 px
       Ih - image height:
            Value:        1704 px
       Xr - X resolution:
            Value:        313.306 px/cu
       Yr - Y resolution:
            Value:        313.306 px/cu
       Pw - pixel width:
            Value:        0.00319176 cu
       Ph - pixel height:
            Value:        0.00319176 cu
    Rated angle of view (h,v,d): (52, 40, 63) deg
    Largest distortion: 0.37 cu (116.4 px, 8.2% of half-diagonal)
 Photograph Standard Deviations:
    Photo 1: P8250021.JPG
       Omega:
          Value:     -39.425743 deg
          Deviation: 0.00886 deg
       Phi:
          Value:     -1.180839 deg
          Deviation: 0.00796 deg
       Kappa:
          Value:     -179.839283 deg
          Deviation: 0.00287 deg
       Xc:
          Value:     0.454890 ou
          Deviation: 0.000162 ou
       Yc:
          Value:     1.793760 ou
          Deviation: 0.000187 ou
       Zc:
          Value:     1.469288 ou
          Deviation: 0.000205 ou
```

```
Photo 2: P8250022.JPG
   Omega:
      Value:     -39.761249 deg
      Deviation: 0.00841 deg
   Phi:
      Value:     -1.846758 deg
      Deviation: 0.00908 deg
   Kappa:
      Value:     -90.121383 deg
      Deviation: 0.00303 deg
   Xc:
      Value:     0.470426 ou
      Deviation: 0.000195 ou
   Yc:
      Value:     2.027243 ou
      Deviation: 0.000224 ou
   Zc:
      Value:     1.638797 ou
      Deviation: 0.000242 ou
Photo 3: P8250023.JPG
   Omega:
      Value:     -27.239490 deg
      Deviation: 0.011 deg
   Phi:
      Value:     -28.565343 deg
      Deviation: 0.00788 deg
   Kappa:
      Value:     -141.846585 deg
      Deviation: 0.00561 deg
   Xc:
      Value:     -0.644455 ou
      Deviation: 0.000197 ou
   Yc:
      Value:     1.466418 ou
      Deviation: 0.000187 ou
   Zc:
      Value:     1.581499 ou
      Deviation: 0.000243 ou
Photo 4: P8250024.JPG
   Omega:
      Value:     -28.558189 deg
      Deviation: 0.00921 deg
   Phi:
      Value:     -30.331722 deg
      Deviation: 0.00937 deg
   Kappa:
      Value:     -49.784451 deg
      Deviation: 0.00488 deg
   Xc:
      Value:     -0.643655 ou
      Deviation: 0.000205 ou
   Yc:
      Value:     1.491033 ou
      Deviation: 0.000207 ou
   Zc:
      Value:     1.637067 ou
      Deviation: 0.000256 ou
Photo 5: P8250025.JPG
   Omega:
      Value:     4.382511 deg
      Deviation: 0.00986 deg
   Phi:
      Value:     -34.669427 deg
      Deviation: 0.00902 deg
   Kappa:
      Value:     -87.136940 deg
      Deviation: 0.00542 deg
   Xc:
```

```
      Value:     -0.670768 ou
      Deviation: 0.000165 ou
   Yc:
      Value:     0.417346 ou
      Deviation: 0.000151 ou
   Zc:
      Value:     1.410399 ou
      Deviation: 0.000191 ou
Photo 6: P8250026.JPG
   Omega:
      Value:     2.097544 deg
      Deviation: 0.0106 deg
   Phi:
      Value:     -34.017520 deg
      Deviation: 0.00846 deg
   Kappa:
      Value:     1.509425 deg
      Deviation: 0.00601 deg
   Xc:
      Value:     -0.713593 ou
      Deviation: 0.00018 ou
   Yc:
      Value:     0.476373 ou
      Deviation: 0.000162 ou
   Zc:
      Value:     1.464831 ou
      Deviation: 0.000211 ou
Photo 7: P8250027.JPG
   Omega:
      Value:     27.348261 deg
      Deviation: 0.00893 deg
   Phi:
      Value:     -28.302938 deg
      Deviation: 0.00914 deg
   Kappa:
      Value:     -44.207908 deg
      Deviation: 0.00466 deg
   Xc:
      Value:     -0.534726 ou
      Deviation: 0.000162 ou
   Yc:
      Value:     -0.349536 ou
      Deviation: 0.000164 ou
   Zc:
      Value:     1.403703 ou
      Deviation: 0.000211 ou
Photo 8: P8250028.JPG
   Omega:
      Value:     26.923258 deg
      Deviation: 0.0109 deg
   Phi:
      Value:     -28.127953 deg
      Deviation: 0.00792 deg
   Kappa:
      Value:     44.866655 deg
      Deviation: 0.00561 deg
   Xc:
      Value:     -0.718941 ou
      Deviation: 0.000222 ou
   Yc:
      Value:     -0.466477 ou
      Deviation: 0.000213 ou
   Zc:
      Value:     1.715075 ou
      Deviation: 0.000275 ou
Photo 9: P8250029.JPG
   Omega:
      Value:     30.389264 deg
```

```
      Deviation: 0.00895 deg
   Phi:
      Value:     0.190661 deg
      Deviation: 0.00812 deg
   Kappa:
      Value:     0.084680 deg
      Deviation: 0.0026 deg
   Xc:
      Value:     0.524910 ou
      Deviation: 0.000169 ou
   Yc:
      Value:     -0.543280 ou
      Deviation: 0.000173 ou
   Zc:
      Value:     1.534216 ou
      Deviation: 0.000207 ou
Photo 10: P8250030.JPG
   Omega:
      Value:     31.007630 deg
      Deviation: 0.0087 deg
   Phi:
      Value:     1.729844 deg
      Deviation: 0.00907 deg
   Kappa:
      Value:     89.539855 deg
      Deviation: 0.00276 deg
   Xc:
      Value:     0.554111 ou
      Deviation: 0.000184 ou
   Yc:
      Value:     -0.593287 ou
      Deviation: 0.000196 ou
   Zc:
      Value:     1.617125 ou
      Deviation: 0.000225 ou
Photo 11: P8250031.JPG
   Omega:
      Value:     27.634202 deg
      Deviation: 0.0111 deg
   Phi:
      Value:     30.750219 deg
      Deviation: 0.0079 deg
   Kappa:
      Value:     42.335735 deg
      Deviation: 0.0061 deg
   Xc:
      Value:     1.770071 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     -0.425193 ou
      Deviation: 0.000188 ou
   Zc:
      Value:     1.552593 ou
      Deviation: 0.000242 ou
Photo 12: P8250032.JPG
   Omega:
      Value:     24.650146 deg
      Deviation: 0.00943 deg
   Phi:
      Value:     30.239455 deg
      Deviation: 0.00984 deg
   Kappa:
      Value:     133.204238 deg
      Deviation: 0.00516 deg
   Xc:
      Value:     1.864899 ou
      Deviation: 0.000209 ou
   Yc:
```

```
      Value:     -0.480971 ou
      Deviation: 0.000207 ou
   Zc:
      Value:     1.614058 ou
      Deviation: 0.000265 ou
Photo 13: P8250033.JPG
   Omega:
      Value:     0.525524 deg
      Deviation: 0.00984 deg
   Phi:
      Value:     33.149801 deg
      Deviation: 0.00904 deg
   Kappa:
      Value:     88.705121 deg
      Deviation: 0.00522 deg
   Xc:
      Value:     1.630631 ou
      Deviation: 0.000171 ou
   Yc:
      Value:     0.497602 ou
      Deviation: 0.000158 ou
   Zc:
      Value:     1.471594 ou
      Deviation: 0.000197 ou
Photo 14: P8250034.JPG
   Omega:
      Value:     -1.739655 deg
      Deviation: 0.0108 deg
   Phi:
      Value:     33.635645 deg
      Deviation: 0.00857 deg
   Kappa:
      Value:     180.202091 deg
      Deviation: 0.006 deg
   Xc:
      Value:     1.796837 ou
      Deviation: 0.000199 ou
   Yc:
      Value:     0.525347 ou
      Deviation: 0.000184 ou
   Zc:
      Value:     1.598322 ou
      Deviation: 0.000227 ou
Photo 15: P8250035.JPG
   Omega:
      Value:     -30.765484 deg
      Deviation: 0.00909 deg
   Phi:
      Value:     28.173051 deg
      Deviation: 0.00932 deg
   Kappa:
      Value:     138.430041 deg
      Deviation: 0.00483 deg
   Xc:
      Value:     1.671657 ou
      Deviation: 0.000185 ou
   Yc:
      Value:     1.554521 ou
      Deviation: 0.000187 ou
   Zc:
      Value:     1.501365 ou
      Deviation: 0.000239 ou
Photo 16: P8250036.JPG
   Omega:
      Value:     -29.885916 deg
      Deviation: 0.0107 deg
   Phi:
      Value:     26.975370 deg
```

```
      Deviation: 0.00791 deg
   Kappa:
      Value:     -134.632252 deg
      Deviation: 0.0055 deg
   Xc:
      Value:     1.694045 ou
      Deviation: 0.000209 ou
   Yc:
      Value:     1.619402 ou
      Deviation: 0.000198 ou
   Zc:
      Value:     1.590016 ou
      Deviation: 0.000263 ou
Photo 17: P8250037.JPG
   Omega:
      Value:     -8.524924 deg
      Deviation: 0.0102 deg
   Phi:
      Value:     -0.516031 deg
      Deviation: 0.01 deg
   Kappa:
      Value:     179.396299 deg
      Deviation: 0.00207 deg
   Xc:
      Value:     0.424528 ou
      Deviation: 0.0003 ou
   Yc:
      Value:     0.823028 ou
      Deviation: 0.000288 ou
   Zc:
      Value:     1.972157 ou
      Deviation: 0.000252 ou
Photo 18: P8250038.JPG
   Omega:
      Value:     -4.780087 deg
      Deviation: 0.00998 deg
   Phi:
      Value:     0.666315 deg
      Deviation: 0.00962 deg
   Kappa:
      Value:     88.786576 deg
      Deviation: 0.00198 deg
   Xc:
      Value:     0.481967 ou
      Deviation: 0.000274 ou
   Yc:
      Value:     0.926766 ou
      Deviation: 0.000293 ou
   Zc:
      Value:     1.885335 ou
      Deviation: 0.000239 ou
Photo 19: P8250039.JPG
   Omega:
      Value:     -4.413731 deg
      Deviation: 0.00965 deg
   Phi:
      Value:     -0.411919 deg
      Deviation: 0.00969 deg
   Kappa:
      Value:     88.244389 deg
      Deviation: 0.00195 deg
   Xc:
      Value:     0.461866 ou
      Deviation: 0.000281 ou
   Yc:
      Value:     0.578854 ou
      Deviation: 0.000284 ou
   Zc:
```

```
            Value:     1.875378 ou
            Deviation: 0.000218 ou
      Photo 20: P8250040.JPG
         Omega:
            Value:     -7.605652 deg
            Deviation: 0.00976 deg
         Phi:
            Value:     -1.556339 deg
            Deviation: 0.0107 deg
         Kappa:
            Value:     -180.050876 deg
            Deviation: 0.00208 deg
         Xc:
            Value:     0.701782 ou
            Deviation: 0.000334 ou
         Yc:
            Value:     0.782358 ou
            Deviation: 0.000276 ou
         Zc:
            Value:     1.926167 ou
            Deviation: 0.000247 ou
      Photo 21: P8250041.JPG
         Omega:
            Value:     -8.697217 deg
            Deviation: 0.00966 deg
         Phi:
            Value:     1.049899 deg
            Deviation: 0.0107 deg
         Kappa:
            Value:     -182.614499 deg
            Deviation: 0.00213 deg
         Xc:
            Value:     0.268718 ou
            Deviation: 0.000328 ou
         Yc:
            Value:     0.821199 ou
            Deviation: 0.000265 ou
         Zc:
            Value:     1.905690 ou
            Deviation: 0.00025 ou
Quality
   Photographs
      Total number: 21
      Numbers used: 21
   Cameras
      Total number: 1
      Camera1:
         Calibration:                   yes
         Number of photos using camera: 21
         Photo point coverage:
            Rectangular: 41%-83% (61% average, 92% union)
            Convex hull: 31%-62% (46% average, 87% union)
            Radial:      60%-92% (73% average, 92% union)
   Photo Coverage
      References points outside calibrated region:
         none
   Point Measurements
      Number of control pts: 4
      Number of object pts: 96
      CP ray count: 21-21 (21.0 avg)
         4 points with 21 rays.
      OP ray count: 16-21 (20.7 avg)
         1 points with 16 rays.
         1 points with 17 rays.
         2 points with 18 rays.
         3 points with 19 rays.
         5 points with 20 rays.
         84 points with 21 rays.
```

```
Point Marking Residuals
   Overall point RMS: 0.226 pixels
   Mark point residuals:
      Maximum: 0.952 pixels (OP 1003 on photo 5)
   Object point residuals (RMS over all images of a point):
      Minimum: 0.101 pixels (OP 67 over 21 images)
      Maximum: 0.569 pixels (OP 1004 over 21 images)
   Photo residuals (RMS over all points in an image):
      Minimum: 0.178 pixels (photo 4 over 97 points)
      Maximum: 0.318 pixels (photo 6 over 93 points)
Point Precision
   Total standard deviation (RMS of X/Y/Z std):
      Minimum: 8.6e-05 (OP 49)
      Maximum: 0.00012 (OP 90)
   Maximum X standard deviation: 5.2e-05 (OP 90)
   Maximum Y standard deviation: 5.5e-05 (OP 90)
   Maximum Z standard deviation: 8.9e-05 (OP 90)
   Points with high correlations
      Points with correlation above 95%: 0
      Points with correlation above 99%: 0
Point Angles
   CP
      Minimum: 83.4 degrees (CP 1003)
      Maximum: 85.8 degrees (CP 1002)
      Average: 84.7 degrees
   OP
      Minimum: 79.6 degrees (OP 90)
      Maximum: 90.0 degrees (OP 47)
      Average: 86.5 degrees
```