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A Comprehensive Workflow to Process UAV Images for the Efficient Production of Accurate Geo-information

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Abstract:

UAV-based remote sensing offers the possibility to acquire aerial images with high geometric and temporal resolutions. With highly automated photogrammetric software packages, this imagery is extensively and quite successfully used for the production of geo-information. However, the utilization of inexpensive, un-calibrated small-format cameras mounted on lightweight UAV makes processing of aerial images challenging. After the automatic measurements of tie points the image orientations and the camera calibration is computed in a bundle block adjustment for compensating systematic effects. The quality and distribution of tie points may be optimized to avoid reconstruction errors before dense point cloud computation. For processing the acquired images, the operator tends to rely on the default parameter values given by the software provider, which may be inadequate. Additionally, inconsistent advises are available in the literature on how to reduce tie point errors correctly and efficiently. Therefore, it is essential to establish a comprehensive workflow to process aerial images for an efficient production of accurate geo-information. Focusing on the commercial software package Agisoft PhotoScan, the impact of possible workflows that include different processes and parameter values, on the accuracy of the resulting Digital Surface Models (DSM) and orthophoto will be presented.

1. Introduction

Unmanned Aerial Vehicle (UAV) based remote sensing is becoming more and more relevant in surveying applications, even for production chains of several commercial mapping companies due to its low-cost and flexibility. Images are acquired with commercial cameras to produce geo-information such as high resolution DSM and orthophotos using highly automated photogrammetric software packages. The workflow consists of automatic tie point measurements for the determination of image orientation and camera calibration using Structure-from-Motion (SfM) or Multi-View Stereo (MVS) algorithms. The image orientations and camera calibration are computed in a bundle block adjustment. The geo-referencing of the sparse point cloud is conducted using either direct geo-referencing and/or ground control points determined by geodetic surveys and measured in the images. Optimizing the image orientations and the alignment of the point cloud to avoid reconstruction errors before performing dense point cloud computation is a challenging step as there is no official guideline on how to reduce and eliminate tie point errors. The same applies to the values attributed to measurement and image observation parameters, such as the associated precision values, which the operator normally uses as the default values given by the software developers.

In this paper, the impact of proposed workflows that include several processes and different parameter values is assessed based on a point cloud generated in PhotoScan as well as the resulting Digital Surface Model (DSM) and orthophoto. The study is conducted in the urban area of *Águeda* municipality, consisting of a typical urban scene including buildings, roads, vegetation and variable terrain structures as well as planar fields. The UAV system Airborne Robotics AIR6 equipped with a commercial SONY ILCE-6000 camera was used for photogrammetric image data acquisition. In addition to considerations on several workflows, specific conclusions are summarized and recommendations are made for improving the quality of geo-information derived from UAV based images and software using SfM-MVS.

2. Comprehensive workflow

In this project, Agisoft PhotoScan Professional in the version 1.4.1 was used to process the UAV imagery. PhotoScan (PS) is an affordable 3D reconstruction software from the Russian company Agisoft LLC (Agisoft, 2018) for the generation of dense point clouds and photogrammetric products such as orthorectified mosaics and DSM derived from images. The professional version of the software can be purchased for $ 3,499. PS has the advantage to provide a simple workflow, from performing bundle block adjustment to calibrate the camera and orientate images after automatic tie point measurements, geo-referencing by measuring ground control points, concluding with the computation of a dense point cloud and requested final products. Yet, information about the computation algorithms used are not available, documentations of results are superficial and the operator has limited possibilities to influence the result by modifying quality parameters in the software. James et al. (2017) reveals that the apparently straightforward PS workflow needs further clarifications in order to ensure a homogeneous quality of the final products. The photogrammetric bundle block has to be refined by identifying and removing outlier points (blunders) (**Fehler! Verweisquelle konnte nicht gefunden werden.**.1) and by defining appropriate weights for tie and control points (2.3.2) as well as compensating the photogrammetric adjustment for possible shutter effects (2.3.3). In the following, a comprehensive workflow is presented, focusing on the error reduction process of tie point measurements, improvement of interior and exterior orientation parameters and rolling shutter compensation. Also the basic processes related to a bundle block adjustment in an arbitrary coordinate system (named Photo Alignment) and the geo-referencing are addressed.

2.1 Photo Alignment

Photo Alignment is a process in PS for image matching and bundle block adjustment in an arbitrary system. It generates a sparse point cloud as well as the interior and exterior orientation parameters of all images in that system, including systematic error compensation such as non-linear lens distortions. Prior to the adjustment, the tie points are automatically measured by detecting and matching features in overlapping images resulting in a sparse point cloud.

2.2 Geo-referencing

The geo-referencing of the sparse point cloud is conducted after Photo Alignment using the coordinates of at least three ground control points (GCP) determined by geodetic surveys. Depending on the requirements, the geo-referencing can be done either using GCP coordinates or camera coordinates (image orientation parameters), or both. In PS, the GCP are named markers and are used in a 7 parameter similarity transformation (3 parameters for translation, 3 for rotation and 1 for scaling). Such a transformation can only compensate a linear model misalignment. The non-linear component cannot be removed with this approach (2.3). This is usually the main reason for geo-referencing errors.
In PS, the GCP coordinate file is imported in the Reference pane. In the reference settings dialogue, the associated coordinate system is defined and the measurement marker accuracy (2.3.2) is set corresponding to the precision obtained in the geodetic point determination. For quality control of the bundle block adjustment in the optimization process (2.3), some of the GCP should be used as check points (CP) instead of control points.

2.3 Optimization procedure

Possible non-linear deformations of the model as referred in 2.2 can be removed by optimizing the estimated point cloud and camera parameters based on the known reference coordinates. During this optimization process, PS adjusts estimated point coordinates and camera parameters minimizing the sum of re-projection errors and reference coordinate misalignment error (2.3.2). To achieve optimal results it may be useful to edit the sparse point cloud by deleting obviously misallocated points beforehand (2.2.1) (Agisoft, 2018). Thus, the optimization procedure includes the following processes:

1- Tie point error reduction
2- Improvement of interior and exterior orientation parameters
3- Compensation of possible rolling shutter effects

In process 1, unreliable tie points are eliminated and in 2, the interior and exterior orientation parameters refined. This procedure is done in an iterative way using the sparse point cloud obtained in 2.2. In this way, high image matching errors of the initial photo alignment, which degrade the quality of the subsequent bundle adjustment results, are removed. This also results in faster computational performance of the subsequent dense point cloud generation. A significantly lower projection error per image is achieved. This can be monitored by the average, as well as for each individual image Root Mean Square re-projection error computed using the tie point image coordinate residuals obtained after block adjustment. Whilst the first is shown in the final report the latter appears in the *Reference* pane next to the number of tie point per image (Agisoft, 2018). An error magnitude, in pixel units of less than 1.0 indicates that an accurate 3D point reconstruction was performed.

There is still neither a comprehensive guideline on how to clean the sparse point cloud on behalf of Agisoft nor a description of the algorithm implemented to do it. Therefore, for a given project, it is imperative to establish a workflow, including the appropriate selection of the parameters involved, sustained on several work presented in the literature (USGS, 2017a; USGS, 2017b; Röder et al., 2017; Agisoft Community, 2012-2018). Different parameters setup and varied processes, such as optional compensation of rolling shutter, might produce different results and thus the presented workflow should be used as a guideline.

2.3.1 Tie point error reduction

After the first determination of the exterior orientation and camera calibration parameters (2.1 and 2.2) it is recommended to clean the sparse point cloud from large tie point re-projection errors. . These errors represent the residuals of the image coordinates, as determined by the matching algorithm and computed by the bundle block adjustment. The cleaning process is conducted by utilizing the *Gradual Selection* tool, which permits to select points based on three criteria as described in detailed below. Their associated parameters can be manually tuned by visualizing the points which the tool accordingly selects to be deleted. The operator can delete these selections based on the parameter values used.

The first criterion, the Reconstruction Uncertainty, allows eliminating points on models with low base-to-height ratios. It is selected in the Gradual Selection dialogue, expressed as a non-dimensional value referring to the directional overlap of photos. Tie points located in the edges of the project area generally have a higher degree of reconstruction uncertainty than those in the block centre, since images covering that area show reduced lateral overlapping (Röder et al., 2017). Such determined 3D points can noticeably deviate from the object surface, introducing noise in the point cloud. While removal of such points should not affect the accuracy of optimization, it may be useful to remove them before building geometry in Point Cloud mode or for better visual appearance of the point cloud (Agisoft, 2018). An uncertainty reconstruction parameter of 10 is the value to be aimed at in the *Gradual Selection* tool since it represents a good base-to-height ratio of 1:2.3 (USGS, 2017a). Based on tests of the authors, the criterion should be used two times to reduce weakest points with poor base-to-height ratios.

The second criterion, the *Projection Accuracy,* allows selecting less reliable tie points. It signalizes poor 3D point determination in relation to stronger ones (Agisoft, 2018). The levels thereby represent statistically weighted values based on image matching relative to the best tie point precisions and therefore don't reflect direct pixel precisions (James, 2017). Poor quality matches are signalized by a high parameter value 'x' which means, that those points have an uncertainty 'x' times higher than the points of minimum uncertainty. These represent high quality matches derived from sharp images (USGS, 2017a). Therefore, the number of poor quality matches, which should be removed, is highly dependent on the quality of the aerial photos. In UAV photogrammetric projects, a parameter value between 2 and 4 is usual as the best achievable result using consumer grade cameras. Therefore, the aim is to achieve a parameter value of 3, although more than three iterations degrade the result as the authors experiences showed. By this, most of the less reliable points resulting from worse matching are removed.

The last criterion *Reprojection Error* is used to remove erroneous points with big residuals. The criterion uses a parameter, given in pixel units, that indicates poor 3D point determination of the corresponding point projections as well as falsely matched points (Agisoft, 2018). It is the parameter with the largest direct influence on the Root Mean Square Error (RMSE) of the control and check points in the *Reference* pane and it can significantly improve the orientation parameters (2.3.2). It is possible to achieve a tie point re-projection error of 0.3 to 0.5 pixels in case of sharp images.

In the cleaning process the threshold is reached either with the targeted parameter values or with the minimum number of tie points of 20% of the original amount, i.e. the image orientation process is completed after a final bundle block adjustment has been performed (2.3.2).

2.3.2 Improvement of interior and exterior orientation parameters

After each tie point elimination, as described in 2.3.1, a bundle block adjustment is performed to estimate new interior and exterior orientation parameters, including lens distortions, using the *Optimize Cameras* tool. After each adjustment, the sum of re-projection errors and control point misalignment errors are minimized (Agisoft, 2018). This can be evaluated in the RMSE results shown on the Reference pane, which were computed using the photogrammetrically and geodetically measured GCP coordinates. After each adjustment update, the next gradual selection can be iteratively performed using the cleaned tie point set. It is recommended to delete not more than 10-20% of the total tie points in every single gradual selection process, since the aim is to just delete points with high re-projection errors. Otherwise the overall photogrammetric point cloud might be over-constraint and the photo alignment can fail, which would be reflected in doming deformations (Röder et al., 2017). The improvement is an iterative process and the impact of each step needs to be carefully checked. While deleting tie points, the number of projections for each single image has to be checked in the *Reference* pane of PS. Having less than 100 projections for each image is not sufficient to perform dense point cloud computation using all images. It is recommended to delete not more than 80% of the points originally calculated during photo alignment to maintain stable relative orientations (Röder et al., 2017).

Bundle block adjustment is executed based on three parameters that represent the precision of observations, used to construct the variance-covariance matrix within the stochastic model. The parameters are located in the *Reference* pane settings dialog and concern the expected precisions of measurements in image and object coordinate systems. Agisoft uses the term 'accuracy' despite the parameters represent precisions rather than accuracies. To maintain consistency, this terminology will be used through this text.

The first parameter, the so called *measurement marker accuracy,* in meters, represents the precision of GCP coordinates in object space. The second parameter, the *projected marker accuracy,* which in turn can be found under *Image coordinates accuracy*, in pixels, is the precision of their measured coordinates in image space. This setting indicates how precisely the GCP were identified and measured by the computer or human operator. The *tie point accuracy,* in pixels, is the third parameter, which is the precision of the image coordinates of tie points (James et al., 2017). These parameters act as weights in the bundle block adjustment. The user must be aware that changing the parameter values can destabilize the whole image block. The given default values are 5.0 mm for *measurement marker accuracy*, 0.1 pixels for *projected marker accuracy* and 1.0 pixel for *tie point accuracy* (Agisoft, 2018).

The *tie point accuracy* parameter is depending on the image quality since tie point positions are estimated on basis of significant features found in the images (Agisoft, 2018). If images are sharp, tie points are accurately localized and the default value of 1.0 pixel may represent a too small weight. The precision values and the weights function in inverse ways - the higher the precision, the bigger the weight. After removal of inaccurate tie points by gradual selection, matching accuracy, which is dependent on the remaining tie points, might reach subpixel level indicated by a reduced maximum image observation residual found in the *Reference* pane. By increasing the tie point accuracy, the photogrammetric block can be prevented from being distorted by the comparatively few control points available, since the numerous tie points are affecting the overall RMS re-projection error. An overfitting by control points would be reflected in a systematic doming deformation and artefacts in the surface model (James et al., 2017). On the other side, a default projected marker accuracy of 0.1 pixels might be too optimistic. While this value can be achieved through automatic measuring, an accuracy of about 0.5 pixels is more realistic for identifying well recognizable features by a human operator. Therefore, it is suggested to decrease the marker accuracy when dealing with natural control points instead of coded targets, which can be automatically detected and measured by the software. This also applies to the geodetic measurement accuracy of markers. A measured precision of 5 mm does not reflect the reality when using GNSS to acquire control points. It leads to unrealistic higher weighting of control points resulting possibly in an insufficient adjustment of the overall bundle block (James et al., 2017). Therefore, an a priori estimation of an appropriate precision for the GCP coordinates corresponding to empirical results of geodetic surveying methods used might lead to more consistent results in the adjustments. Differentiation between horizontal and vertical accuracies of control points is highly recommended for the parameter set-up, since X and Y coordinates are often more accurate than the Z coordinate.

2.3.3 Rolling shutter compensation

Conventional consumer grade cameras with CMOS sensors typically mounted on UAV systems use the rolling shutter technique to obtain better quality and reduce motion blur in photos. The image acquisition principle is to expose the pixels consecutively by either horizontal or vertical line scanning. Consequences of the rolling shutter are visible image distortions in case of image acquisition with a moving camera (Luhmann, 2018). Due to the constant movement of an UAV, the exterior orientation varies within each horizontal sensor line of the image, which has to be compensated for in the bundle block adjustment. Since these distortions are systematic effects, they can be mathematically modelled (Vautherin et al., 2016). Agisoft has included optional correction for rolling shutter effects in PS 1.3 to optimize the adjustment and thus the camera calibration parameters.

3. Implementation of the workflow

The workflow presented above is implemented with a case study conducted in a part of downtown *Águeda*, a municipality situated in the centre region of Portugal. It is one of the largest regions affected by frequent floods in Portugal. Therefore the aim of the project "Flood Forecast and Alert System for the urban area of *Águeda* (FFAS)", under which this work was carried out, is to derive a high resolution digital surface model for flood simulation purposes (Gomes Pereira *et al.,* 2018; Mourato *et al.* 2018). The study area covers 50 ha and is predominately flat. The implementation conveys the testing of different optimization procedures (2.3) in which various processes and parameters values are selected and combined. The impact of the selected processes and parameter values is studied using the corresponding point clouds generated in PS and the resulting surface models to give a comprehensive recommendation about the different optimization procedures.

3.1 Aerial flight and initial photo alignment

An Airborne Robotics AIR6 system was used to acquire the UAV imagery using a commercial Sony ILCE-600L camera with a 16 mm lens. In two flight campaigns at different flight altitudes, 193 photos were acquired - 111 photos at 130 m and 82 photos at 170 m covering the whole area. The average flying speed was 6 m/s and as stated previously, the UAV is not equipped with a navigation system. UAV flights in different heights and/or in additional cross strip patterns introduce additional depth information and support reliable calibration of low-cost UAV cameras (Gerke & Przybilla, 2016; Lindstaedt & Kersten, 2018). Initial photo alignment (2.1) using the option "high" accuracy in PS resulted in ca. 170.000 automatically measured tie points.

3.2 Geo-referencing and check points

A feasible but adequate amount and spatial distribution of GCP has to be chosen to geo-reference the 3D point cloud, surely when no navigation data are available. In this project, the aerial image block is oriented and geo-referenced using only natural distinctive control points. Ten ground control points and 43 check points were acquired using a South S82T GNSS Rover. The GNSS survey was conducted in real-time kinematic mode with acquisition time of four minutes per point using a reference station from the permanent GNSS reference station network of Portugal (ReNEP). An accuracy of 2 cm in planimetry and 4 cm in altimetry were achieved. Nine GCP were distributed evenly along the boundary of the study area while one was placed in the centre of the block. The centre GCP is important since the block could get a concave deformation causing a negative effect on the height value. In PS only 15 of the check points (CP) were involved to assess accuracies of the block adjustment, while 28 independent check points (CPI) were available for further analysis in ArcMap.

3.3 Optimization procedure

In this section, several procedures on how to optimize the block adjustment results are presented. The overall strategy is to perform bundle block adjustment with and without prior tie point reduction. In the first case (1st column in Figure 1, lines 2 till 5), three sets of bundle block parameters are selected to carry out the adjustment after each tie point cleaning operation, except for the last adjustment for which another three sets of parameters are chosen (2nd column in Figure 1). Furthermore, some of these processes are combined with compensation of rolling shutter effects (2.3.3). The first line of the 1st column in Figure 1 concerns a different strategy, named reference optimization procedure, involving only bundle block adjustment after geo-referencing (2.2 and 3.2) without prior tie point cleaning. This procedure is used as reference because is commonly used in practise.
The above referred parameters relate to the marker projection accuracy (ma) and tie point accuracy (tpa) as stated in section 2.3.2. To justify the chosen values it has to be mentioned that in the course of the error reduction, the tie point residual magnitude in image space and visible in the *Reference* pane was improved in all procedures from initially 2.0 pixel to lower than 0.6 pixel. Since the overall RMS re-projection error is defined by the image coordinates of tie points, it stands to reason to choose as well this value for the *tie point accuracy* parameter. For the projection *marker accuracy*, potential values are the default 0.1 pixels and a more realistic value of 0.5 pixels. Besides, the marker measurement accuracy is set in all combinations corresponding to the results of the geodetic field survey method (0.02 m for XY and 0.04 m for Z, "0.02/0.04" in PS).
The process of tie point reduction involves a number of iterations described in section 2.3.1, reaching *Reconstruction Uncertainty*, *Projection Accuracy* and *Reprojection Error* the values 10.2, 3.6 and 0.35, respectively. The improvements of the combinations in Figure 1 are implied by the percentage of the total accuracy variation (RMSE) in the GCP (blue bars) and CP (green bars), compared to the total RMSE of the reference optimization procedure. The XYZ RMSE of this reference optimization procedure is

11.6 cm for GCP and 6.6 cm for CP as presented in the first column in Table 1. Table 1 also shows the RMSE values separated in horizontal and vertical components of the most promising optimization procedures (*orange*, *green* and *red* in Figure 1).

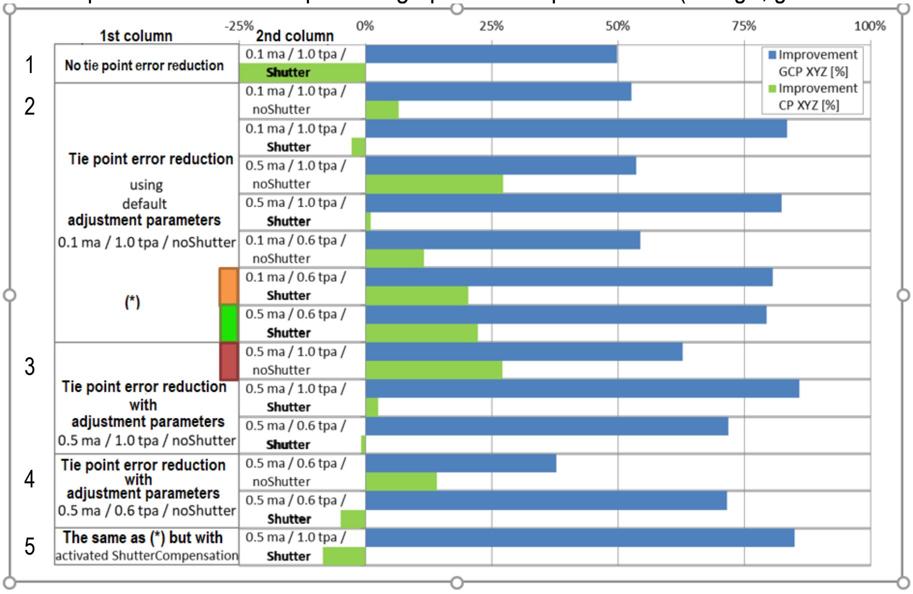

Figure 1 – Presentation of several optimization procedures stating improvements towards the reference optimization one

Table 1 – GCP and CP RMSE of reference and selected procedures as colour-marked in Figure 1

Setup	Count	XY [cm]	Z [cm]	XYZ [cm]
Reference optimization procedure using default adjustment parameters: 0.1 ma; 1.0 tpa; noShutter	10 GCP 15 CP	6.7 4.3	9.5 5.1	11.6 6.6
(orange) Block adjustment with tie point error reduction.Parameters: Initially: 0.1 ma; 1.0 tpa; noShutter / Last adjustment: 0.1 ma; 0.6tpa; Shutter	10 GCP 15 CP	2.0 3.6	1.0 3.9	2.2 5.3
(green) Tie point error reduction using adjustment parameters: Innitially: 0.1 ma; 1.0 tpa; noShutter / Last adjustment: 0.5 ma; 0.6tpa; Shutter	10 GCP 15 CP	1.8 3.2	1.5 4.1	2.4 5.1
(red) Tie point error reduction using adjustment parameters: Innitially:0.5 ma; 1.0 tpa; noShutter / Last adjustment: to 0.5 ma; 1.0 tpa; noShutter	10 GCP 15 CP	2.9 3.1	3.2 3.7	4.3 4.8

The analysis of the results obtained with the tested optimization procedures allows one to state the following:

- activating rolling shutter (RS) compensation has the greatest influence on GCP error reduction. The RMSE in Z is consistently improved by 50-70% for GCP when activating RS compensation in contrast to results obtained when using the reference optimization procedure.
- Using default observation parameter values (ma = 0.1 pix, tpa = 1.0 pix) after tie point error reduction results in a great improvement of the RMSE GCP, while that of CP gets worse (line 2). This implies an insufficient weighting of the parameters in the image space in contrast to that of the control points in object space, because their errors are shifted into the image space while bundle block adjustments. To stabilize the overall photogrammetric block, those parameters should be adjusted.
- In the phase of tie point error reduction, the *tie point accuracy* parameter should be left to the default value of 1.0 pixel. Otherwise, the model will be overly fitted since the RMSE for CP were worse when bundle adjustment was executed with other parameters (see line 4).
- The same applies for activating RS compensation initially (line 5). It leads to a decrease of CP RMSE while that of GCP is improved greatly and therefore implies a strong weighting. RS compensation should be applied after tie point error reduction, if realistic marker accuracy values are used and only if the flying speed of the UAV is significant high (Vautherin et al., 2016).
- When setting ma = 0.5 pix and performing tie point error reduction, the values of the RMSE of GCP and CP are of the same order when deactivating RS compensation (*red* marked row in Table 1). The surpassing high errors in GCP, compared to *orange*

and *green* in Table 1, imply that they are not given adequate weighting. The DSM has to be further examined in order to interpret this result (section 3.3.1).

- the optimization procedures marked in *orange* and *green* in Table 1 show great improvements in GCP as well as CP RMSE.

3.3.1 Discussion of promising optimizing procedures

The promising optimizing procedures, colour marked in *orange*, *green* and *red* (see Figure 1 and Table 1), are discussed in much more detail in the following. The accuracy assessment made using the DSM and the results of the bundle adjustment in PS is presented in Figure 2 and Figure **3**. The results in Figure 3 shows that the *red* optimization procedure degrades the overall accuracy by having correlating high accuracy values in GCP and CP. The deformation of the overall model is represented by the smaller GCP accuracy when using the DSM. The o*range* and *green* procedures result in low RMSE, i.e., between 6 and 7 cm as computed using the DSM (Figure 2). For procedure in *orange*, the ratio between DSM and PS RMSE values in XYZ is around 3.0 for the GCP (6.9 cm in DSM vs. 2.3 cm in PS) and 1.2 for the CP (6.1 cm in DSM vs. 5.3 cm in PS). The models are consistent when performing tie point cleaning and setting the parameters as shown in the o*range* and *green* procedures, which is also shown by the achieved accuracies of the independent check points (CPI).

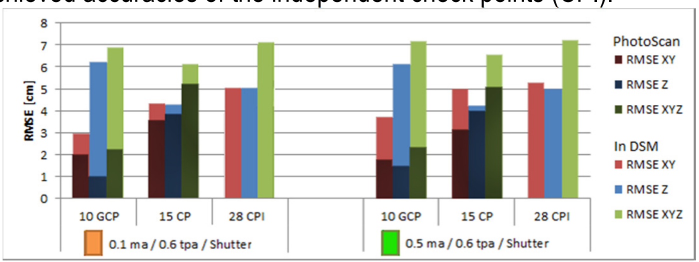

Figure 2 – RMSE of GCP and CP in PS and derived from DSM, optimized with default parameters (ma = 0.1, tpa = 1.0)

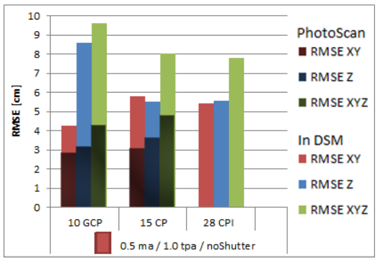

Figure 3 – RMSE of GCP and CP in PS and derived from DSM optimized with ma=0.5, tpa=1.0, no rolling shutter

3.3.2 Rolling shutter compensation

Since the SONY ILCE-6000 used in this project is a conventional camera with CMOS sensor and rolling shutter, the possible gains of compensating for rolling shutter effects has to be further discussed. Figure 4 shows the assessment of the quality of a DSM, in terms of RMSE, produced in PS using three control point configurations with and without RS compensation during the bundle adjustment process. The GCP configurations are the following: (a) 28 GCP spatially distributed for conventional aerial triangulation (one GCP each two bases all around the photogrammetric block and longitudinal chains of GCP connecting each strip), (b) 10 GCP around the photogrammetric block and one in the centre, (c) 6 GCP in the corners of the block and one in the block centre. The point clouds were optimized according to the *orange* marked procedure described in section 3.3. The RMSE in Z is computed using 28 CP measured in the DSM whilst those in X and Y are computed using the orthophotos. Standard deviations varied from between 0.3 cm for deactivated RS and around 0.5 cm when activating RS compensation, which means that there are no bias. Activating RS compensation has a major impact on the height component accuracy by consistent improvements of 2 cm in all cases. The horizontal RMSE is just significantly improved when using a minimum amount of control points (6 GCP) from 6.9 cm to 5.8 cm. The impact of RS compensation seems to be dependent on the quantity and spatial distribution of control points, which is also stated by Lindstaedt & Kersten (2018). It is concluded, that RS compensation can provide an accuracy improvement of the vertical coordinate, only if the speed of the UAV during the flight is significant high.

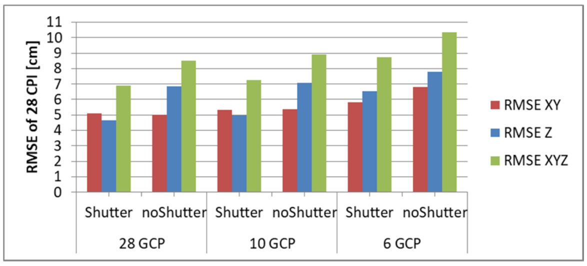

Figure 4 – Results of accuracy assessments using different GCP configurations for bundle adjustment, including compensation of possible RS effects

4. Conclusions & Outlook

The potential improvements in the overall accuracy of UAV photogrammetric projects by optimization of the bundle block adjustment parameters were demonstrated. Tie points of low matching quality and having high re-projection errors have to be identified and removed prior to bundle adjustment in an iterative process. The last adjustment has to be executed with refined parameters related to the precision of observations. The precision of the image coordinates of tie points affect the overall RMS re-projection error. It can strengthen the photogrammetric block when it is smaller than 1.0 pixel. The confidence in tie points and therefore in the SfM based measurements depends on the image quality in hand and their percentage of overlap, as well as on a comprehensive elimination of re-projection errors to only maintain high quality point matches. The definition of the tie point precision values can be guided by considering the maximum image observation residual that should be limited to subpixel range after tie point error reduction. Using 0.5 pixels as the precision for identifying and measuring control and check points, results also in a consistent point cloud. Since an uncalibrated conventional camera with CMOS sensor and with rolling shutter technique has been used in this UAV project, the compensation for possible rolling shutter effects in the calibration process is suggested. It could be verified that for the predominately flat study area, accuracy improvements in the height component were attained. Agisoft does not provide an official guideline on how to utilize the tie point reduction tool. In addition, they recommend the same default adjustment parameter values regardless the given project conditions. The underlying photogrammetric processing of PhotoScan is still not fully comprehended and in order to unlock the potential of a project-related optimization process, further investigations are required. The workflow described in this paper led to a significant improvement of the final photogrammetric block accuracy and evolves from published work using different amount of images and image quality, control point distributions and surface topography, which are parameters influencing the quality of identifiable and measurable tie points and GCP. To increase knowledge, published UAV work should clear state the workflow, including the parameter values used for bundle block adjustments. An accuracy assessment should also be conducted in the desired final product, which in several applications is a digital surface model in combination with orthophotos. Performing this independently from results of the SfM-MVS processing software, supplies a comprehensive statement about the quality of final photogrammetric products.

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