

DIGITAL SURFACE MODELS FROM ULTRACAM-X IMAGES

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ABSTRACT:

UltraCamX is the newest large format digital aerial camera system by Microsoft Photogrammetry (former Vexcel) and was introduced in 2006. We present a short technical overview about the sensor and we show results from a data experiment. Images from this sensor were produced at high overlaps and used to create digital surface models. In this paper the geometric accuracy of the digital surface data and the quality of UltraCamX images are presented.

UltraCamX offers to capture one frame at an interval of 1.35 seconds. This allows to producing images at high overlaps at large scale and reasonable speed of the aircraft. For the data experiment a ground sampling distance of 10cm was produced at a forward overlap of 90%. Such redundant image data can be used to improve automation and robustness during the processing of dense surface models.

1. INTRODUCTION

Overlapping images are one important source data set for three dimensional object reconstruction and surface modeling. This application - known as "shape from stereo" – does rely on the quality of the source images. Geometric accuracy and radiometric bandwidth are the two most important requirements which are requested in order to produce quality results. Since a few years large format digital aerial cameras are available and did find their way into the photogrammetric production. It was very obvious that the digital sensor did show advantages over film based, scanned images. The most important advantage can be seen in the radiometric quality, thus no longer film grain noise affects the matching process.

Another advantage of digital sensors can be seen in the new all digital workflow excluding the expensive and time consuming handling of the film. Digital image data can be produced and stored at very attractive costs. Therefore the acquisition of data capture may be reorganized. Not the minimum of images but redundancy and robustness are the requirements of the all digital photogrammetric projects.

The new digital sensor system by Microsoft, the UltraCam X was used to capture images over a well known project area. Digital surface information was extracted from UltraCamX images by means of image analysis. The project area of Gleisdorf was mapped at a ground sampling distance (GSD) of 10 cm at a special flight pattern of high overlap. 9 lines are flown in N-S direction, with each about 31 images and 5 lines in the E-W direction, with about 25 images. The project is flown with 80 % forward overlap and 65% side overlap.

We present the quality of the resulting Digital Surface Model (DSM) datasets. From one test flight one DSM was derived from the North to South flight lines and one from the East to West flight lines. The resulting DSMs are compared with Ground Control Points (GCP) in the area and z-Differences are shown.

1.1 UltraCam X

The UltraCam X large format digital aerial camera system was introduced in 2006 and can be seen as the successor of Vexcel's UltraCam D. The basic concept of the design did not change. The sensor unit consists of eight camera heads. Four camera heads are responsible for the large format panchromatic image, another set of four camera heads contribute with four color bands in red, green, blue and near infrared. The sensor produces images of 14430 by 9420 pixels at a frame rate of 1 frame in 1.35 seconds. Thus high overlaps of 80 % along track can be achieved at 5 cm GSD and a reasonable speed of the aircraft. The physical dimension of the image is 103.9 mm by 67.8 mm at a Pixel size of 7.2 μm . The principal distance of the camera is 100.5 mm.



Fig. 1: UltraCam X digital aerial camera system with the Sensor Unit (right) and the airborne Computing Unit including two removable Data Units (left).

The data storage system of the camera offers storage space for almost 4700 frames, thus the system is well prepared for intensive image harvest at large scales and at high overlaps. All image data are initially stored at 16 bit bandwidth (see Fig. 1).

1.2 Basic source data

During the routine delivery process every UltraCamX camera systems has to pass a specific test flight which is performed over the test field of Gleisdorf near Graz. Figure 2 shows an overview of the flight plan for that area. The size of the Gleisdorf test field is about 5 km by 7 km. It shows a huge diversity of cultivation including build up areas, traffic infrastructure, agricultural plans and forests. The ground truth consists of 56 full ground control points and a local GPS station.

The source data sets for our DSM quality assessment consist of images taken at a ground sampling distance of 10 cm at a flying height of 1400 m above ground level. The forward overlap was set to 80% the side lap was set to 65% resulting into a distance between flight lines of 500 m and a base length of 200 m. This special flight pattern supports redundancy and thus automatic blunder detection. Flight lines facing north to south and flight lines facing east to west were used to produce two different sets of DSMs.

During the flight mission GPS/IMU information was collected.

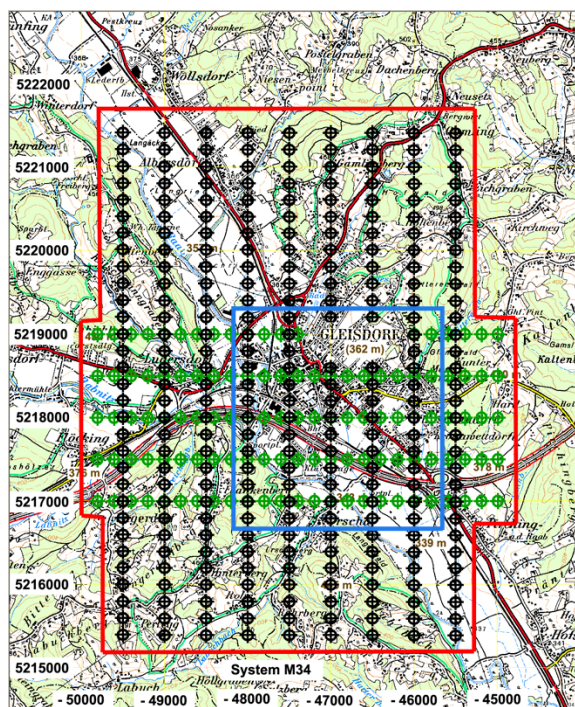


Fig. 2: Overview of the Gleisdorf area with flight lines in two directions and 500 m spacing. The base distance between photo centers is 200 m. The DSM area is marked up by the blue quadrangle.

The size of the source images of the UltraCamX camera system is 14430 pixels cross track and 9420 pixel along track, thus a footprint of 1443 m by 942 m is covered by one frame at a flying height of 1400 m. The single base distance between two images is 200 m, thus the resulting base to height ratio is only 1/7. Therefore a set of three or more images is used for every point measurement. This leads to a base to height ratio of 1/3.5, 1/2.3 or even 1/1.75 and increases the vertical quality and the robustness of the set.

Fig. 3 shows one single frame of the camera system. The sub area on the right gives an impression of the level of detail and the radiometric quality of the image.

The flight mission took place on May, 10th of 2007.



Fig. 3: Source image from UltraCamX at a format of 14430 by 9420 pixels. The entire frame is shown on the left, the detail on the right covers a footprint of 68 by 90 meter.

1.3 The workflow

The entire photogrammetric process consists of the three basic steps of source data acquisition including the post-processing of the raw image data, geo referencing of the images based on GPS/IMU supported aerial triangulation and DSM computation by means of dense image matching.

The post processing is done by the camera specific software package OPC (Office Processing Center) and converts the set of 13 raw sub images of each frame into one single large format panchromatic image and one four band color image. This process includes the so-called stitching between overlapping sub images and also introduces the parameters of the laboratory calibration data set. Such post processed and therefore geometrically and radiometrically corrected images are then introduced into the aero triangulation. The automatic atriangulation (AAT) is performed by using the Match AT software product from INPHO GmbH, Stuttgart, Germany. A camera specific bundle adjustment is then added by using the BINGO software product from GIP, Aalen, Germany. The GPS and IMU processing was supported by IGI mbH, Kreuztal, Germany.

After the images are geo referenced a refined AT is computed and matching points are extracted. These procedures give additional information on the accuracy of the AT, used for the DSM computation in the next step. The DSM algorithm was especially developed for processing UltraCam images. A hybrid multi-view matching algorithm is used for calculating height field images. In a first stage a coarse matching and a dense matching is done to create overlapping range images. In a second stage those overlapping images are fused to non-overlapping height field images which result in the final DSM. Fig. 4 shows the resulting DSM of the central Gleisdorf area. Within this area six small samples were chosen to investigate the quality of the digital surface models. The positions of these samples are marked up in Fig. 4.

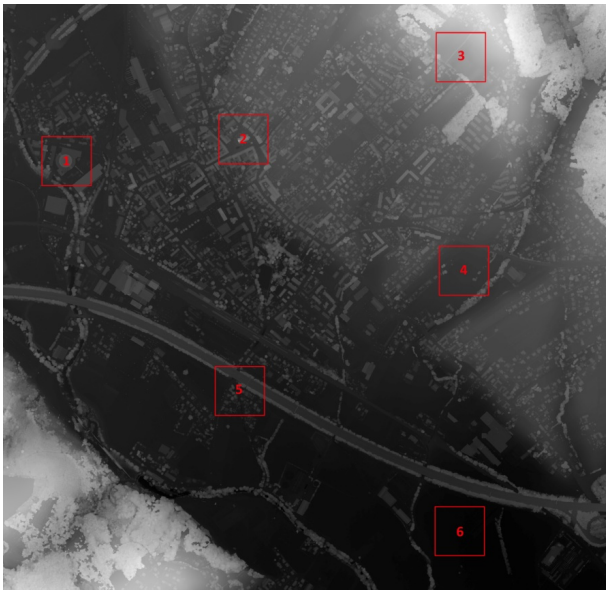


Fig. 4: DSM of the central Gleisdorf area including the six samples for detailed analysis.

2. DETAILED ANALYSIS AND RESULTS

The following analysis is performed in order to investigate the accuracy of the entire photogrammetric process and the resulting DSM data sets. The first quality measure of the process can be given from aerial triangulation. Then we compare the DSM data derived from the two sets of images taken under the different flying direction North to South vs. East to West (NS data set and EW data set).

All available image data from the flight missions show a GSD of 10 cm. The DSM datasets were processed at a mesh size of 20 cm, thus the DSM grid spacing corresponds to two pixels of the source images.

Matlab (The MathWorks, Inc.) was used to compute the specific test data and the height profiles. The overlay of checkpoints and DSM was performed in ESRI ArcGIS.

2.1 Aerotriangulation results

The aerotriangulation process includes the automatic tie point matching based on a manifold of up to 15 images for each of the two data sets, the manual measurement of ground control points in the images and the adjustment of the redundant set of observations by means of the least squares method. This process was done by using the MatchAT software product. In addition to this a camera specific set of auto calibration parameters was introduced and estimated by using the BINGO software package.

The small image distortions which were computed during the auto calibration were then introduced into the image post processing and therefore the geometric image quality and the DSM computation could be improved.

Sensor	Project		Accuracy	
	GSD (cm)	HAGL (m)	Sigma _o (µm)	Rmse z (m)
UCX	10	1400	0.80	0.035

Table 1. Overview of the main AT parameters and results. The good vertical accuracy corresponds to relative accuracy of 1/40 000.

2.2 Comparing the DSM datasets against ground truth

The initial test of the geometric quality of the DSM data was performed by comparing DSM data vs. ground truth. For this test a subset of 16 GCPs of the Gleisdorf area was selected and back projected into the DSM data sets. The vertical value of the DSM mesh near to the specific GCP was then extracted and compared against the z coordinate of the GCP. The results correspond to the expectations from the good results of the aerial triangulation. The standard deviation of the 16 height differences (13 differences in the case of data set NS) was in the range of 1 pixel (~ 10 cm).

PN	Z GCP	Z NS	zDiff NS	Z EW	zDiff EW
P 1	352.688	352.510	0.178	352.518	0.170
P 2	367.966	367.823	0.143	367.843	0.123
P 3	361.062	361.032	0.030	361.002	0.060
P 4	384.855	384.771	0.084	384.702	0.153
P 5	373.465	-	-	373.490	-0.025
P 6	359.916	359.889	0.027	359.884	0.032
P 7	349.424	349.423	0.001	349.389	0.035
P 8	348.021	348.001	0.020	347.896	0.125
P 9a	352.230	352.097	0.133	352.140	0.090
P 9b	352.594	352.656	-0.062	352.532	0.062
P 10	348.227	348.248	-0.021	348.233	-0.006
P 11	364.108	-	-	364.125	-0.017
P 12	360.394	-	-	360.509	-0.115
P 13	344.379	344.457	-0.078	344.380	-0.001
P 14	342.803	342.938	-0.135	342.956	-0.153
P 15	345.585	345.837	-0.252	345.751	-0.166
		MIN	-0.252		-0.166
		MAX	0.178		0.170
		Mean	0.005		0.023
		Stdev	±0.119		± 0.102

Table 2. Comparison of z-Values of two different DSM datasets against check points of the Gleisdorf area (all data given in meter).

Table 2 lists all GCPs with their given z-values (Z GCP) and the corresponding z-Values extracted from the two DSM datasets (Z NS and Z EW). The two additional columns show the differences between Z GCP and z-values from the DSM (z Diff NS and z Diff EW). Finally Table 2 presents minimum and maximum value, mean value and standard deviation which were computed from the set of vertical differences. The relative accuracy in z corresponds to 1/12000 for data set NS and 1/14000 for data set EW. The location of the 16 GCPs is shown in Fig. 5.

Comparing the z-values of the two DSM data sets at the 13 positions of the common GCPs we computed a mean difference of 0.035 m (1/3 of a pixel) and a standard deviation of 0.064 m. Interpreting the mean difference as a global offset we reduced this value from each height difference. The standard deviation of that set of 13 values was then only 0.053 m which is about 1/2 of a pixel of the source images.

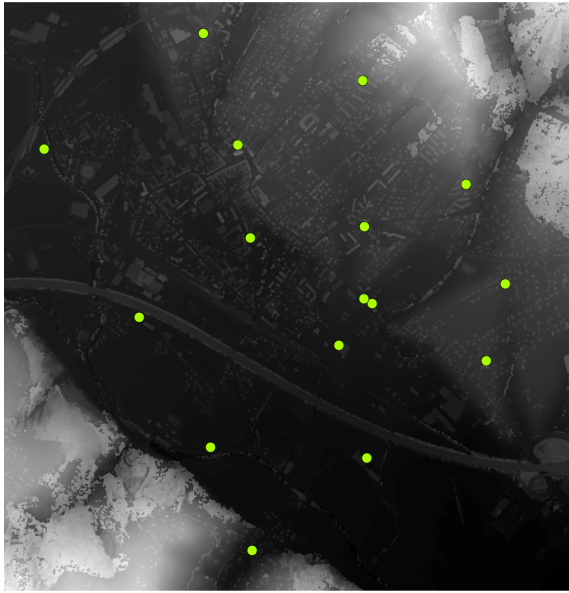


Fig. 5: Set of 16 GCPs mapped onto the DSM of the Gleisdorf area.

2.3 Comparing DSM datasets and measured z-values

For this test manually measured points were used to proof the quality of the DSM in local regions (sample areas). The measurements were done within the Match AT software package and the coordinates of the selected points were computed by means of a bundle adjustment.

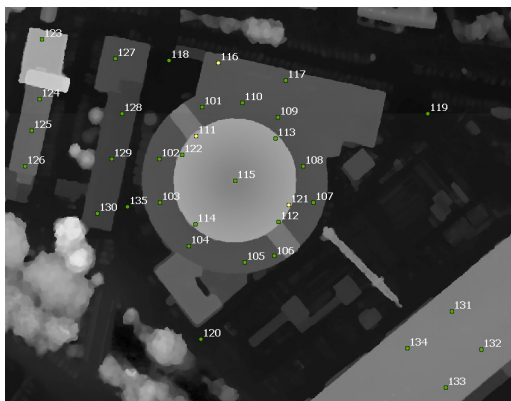


Fig. 6: Sample area 1 showing different buildings of an industrial site. A set of 35 points was measured in the two DSM datasets and z values were compared.

The result of this test is presented in Table 3. The two sets of 35 points show vertical differences of a magnitude of less than 1 pixel (StdDev of ± 0.069 m and ± 0.058 m). Differences between measured values and values extracted from the DSM data sets were used for this test. The two points 115 and 125 did show larg differences in the NS DSM data set and were rejected.

Point	Zmeasured	Z NS	DiffNS	Z OW	DiffOW
101	357,128	357,125	0,003	357,165	-0,037
102	357,190	357,159	0,031	357,174	0,016
103	357,167	357,134	0,033	357,213	-0,046
104	357,135	357,140	-0,005	357,167	-0,032
105	357,153	357,211	-0,058	357,160	-0,007
106	357,195	357,127	0,068	357,158	0,037
107	357,101	357,070	0,031	357,129	-0,028
108	356,962	356,951	0,011	356,998	-0,036
109	357,143	357,126	0,017	357,166	-0,023
110	357,102	357,057	0,045	357,147	-0,045
111	366,191	366,109	0,082	366,089	0,102
112	366,088	366,064	0,024	366,115	-0,027
113	366,038	366,096	-0,058	366,057	-0,019
114	366,047	366,067	-0,020	366,019	0,028
rej. 115	365,231	364,450	0,781	365,25	-0,019
116	357,126	357,263	-0,137	357,305	-0,179
117	357,362	357,352	0,010	357,336	0,026
118	350,969	350,859	0,110	351,011	-0,042
119	350,729	350,787	-0,058	350,749	-0,020
120	351,326	351,365	-0,039	351,291	0,035
121	366,190	366,022	0,168	366,076	0,114
122	366,114	366,055	0,059	366,153	-0,039
123	365,061	365,118	-0,057	365,148	-0,087
124	359,020	358,919	0,101	359,053	-0,033
rej. 125	359,007	359,915	-0,908	359,100	-0,093
126	359,044	359,026	0,018	359,048	-0,004
127	356,462	356,359	0,103	356,412	0,050
128	355,258	355,218	0,040	355,230	0,028
129	355,252	355,238	0,014	355,240	0,012
130	355,243	355,231	0,012	355,296	-0,053
131	362,021	361,912	0,109	361,968	0,053
132	362,059	361,957	0,102	362,118	-0,059
133	362,056	362,116	-0,060	362,003	0,053
134	362,034	361,963	0,071	362,121	-0,087
135	350,914	350,866	0,048	350,880	0,034
		MIN	-0.137		-0.179
		MAX	0.168		0.114
		Mean	0.025		-0.010
		StdDev	± 0.069		± 0.058

Table 3: Z-coordinate values of 35 points are computed from manual image measurements and compared to Z-values from DSM data sets. All units are meter. Point 115 and 125 were classified to be out layers and were rejected.

2.4 Comparing DSM datasets computed from different sets of aerial images (flying directions NS vs. EW)

In the following section we show the vertical differences of six sample areas (cf. Fig. 4) computed from the two DSM data sets. Each sample area consists of 1 000 000 height values, the size of each area is 200 m by 200 m. Each area has a specific kind of cultivation. Sample area 1 consists of industrial buildings with flat roofs, area 2 consists of residential buildings in the center of the village of Gleisdorf including the gothic style church, area 5 includes parts of a motor highway and area 3, 4 and 6 are a mixture of agricultural flat land and forest areas.

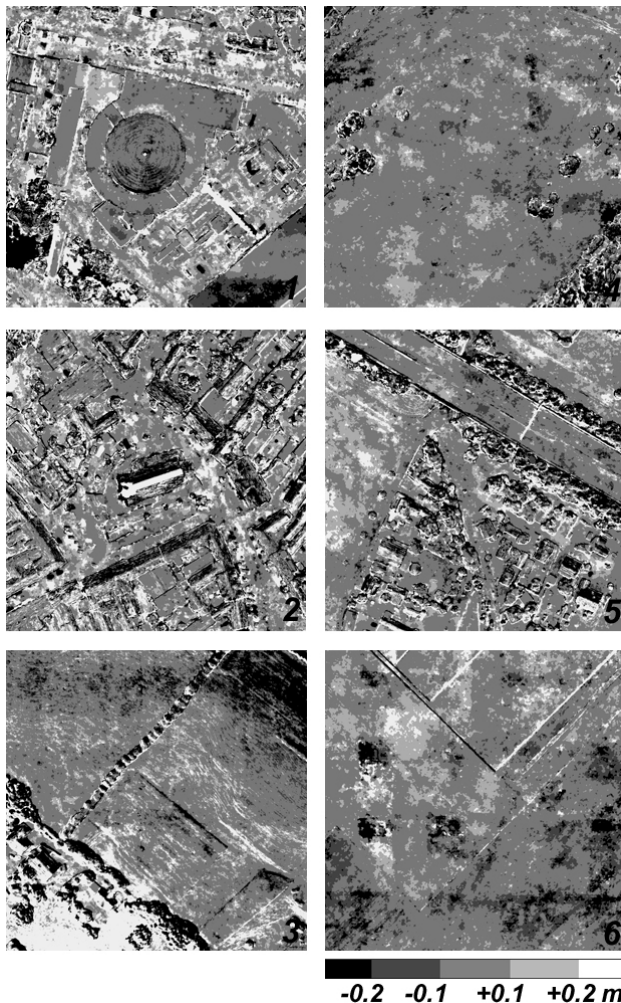


Fig. 7: Sample area 1 to 6 and the height differences computed from the two DSM data sets. Height differences are coded by different grey levels representing 5 classes of magnitude.

Sample	$ Dz < 0.3 \text{ m}$	$ Dz < 0.2 \text{ m}$	$ Dz < 0.1 \text{ m}$
1	86.4 %	74.9 %	45.8 %
2	81.6 %	70.0 %	43.4 %
3	84.2 %	74.2 %	50.0 %
4	96.1 %	93.2 %	73.1 %
5	85.1 %	76.5 %	49.9 %
6	97.7 %	91.7 %	60.9 %
1 to 6	88.5 %	80.1 %	53.9 %

Table 4: Vertical differences within each sample area are mapped into three classes. The classes represent maximum height differences of 0.3 m, 0.2 m and 0.1 m.

The comparison of the 1 000 000 height values of each of the 6 sample areas offers a measure of the noise of the dense DSM data sets. Table 4 shows, that more than 50 % of the vertical differences are smaller than 1 pixel (0.1 m) and more than 80 % are smaller than 2 pixels (0.2 m). It is also obvious, that edges of buildings, forest areas and moving objects (cars on the highway) have their specific impact on the data set. In order to overcome that issue and compute a more meaningful quality measure of the vertical differences of the two DSMs, profiles were defined and height differences along such profiles were investigated. A vertical profile through sample area 4 shows a magnitude of 0.1 m to 0.15 m and a standard deviation of $\pm 0.075 \text{ m}$. The total number of observations is 1000.

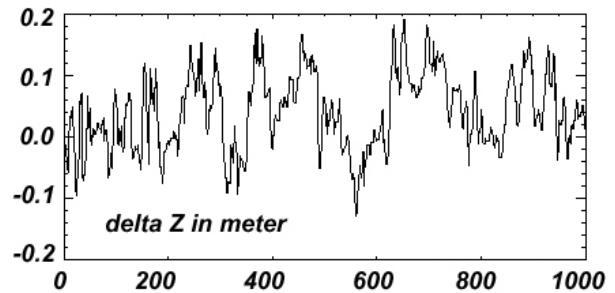


Fig. 8: Vertical profile through sample area 4. The magnitude of vertical differences of the two DSM data sets is illustrated.

3. DISCUSSION

In this contribution we use two sets of digital aerial images from a flight mission over a test area. Different flying directions (North to South vs. East to West) were planned for the aerial mission and images were taken at large overlaps. Exterior orientation data were derived through the aerial triangulation procedure. Based on the two sets of images a dense DSM at a mesh size of 20 cm (2 Pixels) was computed. The quality of the two DSM data sets was investigated by

- Comparing ground truth and DSM data
- Comparing manually measured height values and DSM Data
- Comparing the two DSM data sets.

The quality level of the aerial triangulation was quite high. A σ_o value of $\pm 0.8 \mu\text{m}$ (1/9 pixel) could be achieved. The standard deviation of z values computed from the bundle adjustment was at a 1/3 pixel level ($\pm 0.035 \text{ m}$). When comparing the vertical values of the DSMs with the ground control points we observed differences with standard deviations of $\pm 0.12 \text{ m}$ and $\pm 0.10 \text{ m}$ (~ 1 Pixel).

The vertical accuracy within a smaller sample area was then investigated by comparing manual measurements and DSM data. From a set of 35 points we computed a standard deviation of the vertical differences of $\pm 0.069 \text{ m}$ and $\pm 0.058 \text{ m}$ which is 70 % of the GCP vs. DSM test.

Comparing these results it looks like if the overall vertical accuracy of the DSM datasets is about 1/3 and the local DSM accuracy is about 1/2 of the accuracy of the highly redundant aerial triangulation

In addition to the point to point tests of the digital surface models we have compared the two DSMs through six selected sample areas and observed larger variations in the resulting quality measures. Depending on the kind of cultivation or vegetation we observed about 50% of the height differences less than 0.1 m, 80% less than 0.2 m and almost 90% less than 0.3 m. Problems raised with any kind of larger or smaller forest areas as well as buildings and other man made objects with discontinuities of the digital surface. Such discontinuities caused differences in z not as an indicator for inaccurate height measurements but more for a lack of coincidence of the horizontal positions of the discontinuity in the two DSM data sets. However, these effects have been ignored during our tests.

4. FUTURE WORK

The overall accuracy of the DSM data computed automatically from UltraCam images is very promising. Even if space for improvement is still there we see that such data have a value within several applications like digital ortho image production or 3D object reconstruction. Figure 9 gives a small insight view on how such orthophotos can look like. The resulting ortho image sample has a GSD of 10 cm and was produced on top of the DSM at 20 cm mesh size. The sample was processed completely automatically without any manual interaction.



Fig. 9: Samples of a automatically processed orthoimage of the central area of Gleisdorf.

Beyond the ortho image production the dense DSM data is the basic dataset for any three dimensional city modeling task as the Virtual Earth Initiative of Microsoft. About 100 US-cities extracted from UltraCam aerial images are already online on Virtual Earth. One example among many others is the city of Philadelphia (cf. Fig. 10).

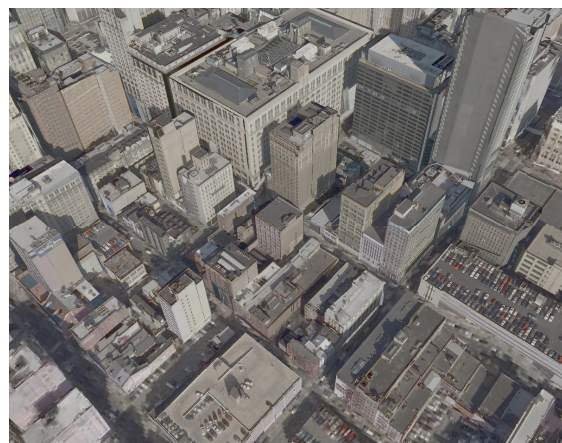


Fig. 10: 3D model of the city of Philadelphia, automatically computed from UltraCam images at high overlap.

The three dimensional digital model of the city was extracted automatically from UltraCam images, the single source for geometry and photo texture. The images were taken at high overlap, enabling automatic, redundant and robust processing.

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