OBLIQUE AERIAL PHOTOGRAPHS - AN “OLD-NEW” DATA SOURCE

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ABSTRACT

New imaging platforms, progress in digital cameras, the use of GNSS/IMU technology either in direct sensor orientation or in integrated sensor orientation, new thinking with regard to control information in georeferencing, and co-operation between two disciplines – photogrammetry and computer vision – have brought the possibility of using oblique aerial photographs as a data source into the limelight. This article sheds light on the history of oblique aerial photographs, gives information about related practical experiences, and envisions the possible near future related to this new-found photogrammetric data product. An important new finding of this study is the use of time-series of oblique photographs for enabling image orientation in structure-from-motion software.

1. INTRODUCTION

The art of photogrammetry started in a terrestrial form, and much of the early development was based on horizontal and oblique photographs (Slama, 1980). Although man reached the sky in hot-air balloons already in the late 18th century, the start of aerial photogrammetry can be dated in 1850s. In 1852 Laussedat produced a map from photographs and experimented with aerial photography in 1858 (Lyon, 1959). Tournachon became the first aerial photographer (Slama, 1980) and the first aerial oblique photograph was taken by Black in 1860 (Rupnik et al., 2014). Image quality has been pursued right from the beginning – Tournachon was awarded a patent for keeping the camera vertical and stable (Slama, 1980). C. B. Adams, a US army officer, patented a method of making maps from vertical photographs; the method is nowadays known as the radial line method of control extension (Lyon, 1959). Another US army officer, S. Reber, introduced an extension of Adams’s method in 1896, which was designed for oblique photographs. Oblique imaging geometry was utilised by some cameras in the early 20th century, such as Scheimpflug’s 8-lens camera, Aschenbrenner’s 9-lens camera and Reading’s 9-lens camera (Slama, 1980). Perhaps the best known utilisation of oblique aerial photography in mapping is the Canadian grid method (Wolf, 1974). In military use, oblique imagery has been one of the key imaging tools from its inception.

The definition of an oblique image is that it has been intentionally taken tilted at least 10 gon from the plumb line (Thompson, 1966). In addition, oblique images can be classified as high obliques or low obliques, in respect of whether the horizon is visible in the image or not, respectively (Slama, 1980). The majority of civil photogrammetric missions since the 1940s have been conducted with vertical aerial imagery. The advantages of vertical images are their more meaningful conversion to orthographic projection, more uniform occlusion throughout the image, more constant image scale, and perhaps the easier interpretation of structural
objects. Some pros for obliques are the easy object recognition for laymen, the visibility of vertical structures, and their larger footprint. In a convergent-low-oblique setup, in which oblique cameras image fore and aft, the base-height ratio can be increased to yield better height accuracy in stereoscopic data capture (Slama, 1980). The new appearance of oblique imagery happened temporally quite close to the transition to the digital camera era over a decade ago.

There are many applications that can utilise the potential of oblique aerial photographs. Situations where side views of manmade structures are needed are particularly well suited to oblique photography. Xiao et al. (2012) presented a method for building detection and reconstruction based on airborne oblique photographs. Fritsch and Rothermel (2013) demonstrated dense image matching of nadir and oblique aerial photographs with two imaging systems, and gave recommendations for increased overlaps compared to the usual overlaps in aerial photogrammetry. Meixner and Leberl (2011) studied building floor and window classification accuracy as a function of tilt angle, the best values occurring in the range of 20° to 27°. In an earlier study, Meixner and Leberl (2010) concluded that the need for oblique imagery is not a necessity if high overlap vertical imagery is available. Other infrastructure-related oblique imagery studies have been published by Gruber and Walcher (2013), Nyaruhuma et al. (2012), Murtiyoso et al. (2014), Wang et al. (2008), Jurisch and Mountain (2008), and Prandi et al. (2008). Other applications that may benefit from oblique aerial imagery are land administration (Kisa et al., 2013; Lemmens et al., 2008), monitoring of dangerous sites (Marsella et al., 2014), coastal studies (Harwin and Lucieer, 2012), forestry (Lisein et al., 2013), emergency services (Artés, 2006) and structural damage assessment (Gerke and Kerle, 2011). With regard to applications of aerial oblique video images, Zhang et al. (2005) tested them for 3D city modelling, Rasika et al. (2006) and Kerle and Stekelenburg (2004) for disaster-induced damaged area classification, and Kumar et al. (2001) for aerial surveillance. Studies with historical images have been done by Nurminen et al. (2015), Vassilaki et al. (2012), Nocerino et al. (2012) and Redecker (2008) for example; in the last two of these studies oblique and split vertical imagery were mentioned.

In this article, the state-of-art with regard to oblique aerial images is reviewed, important opportunities are highlighted, and test results presented. The most important finding of this article is the use of an oblique image time-series in a suburban area to enable image orientation with structure-from-motion software. In many organisations around the world there are dormant oblique image archives that contain valuable raw data for highly automatised modern point cloud creation software. Imagery captured for other reasons in the past may be well suited for point cloud creation. The greatest opportunities for oblique time-series are in urban areas, where buildings and structures may remain relatively unchanged for decades, thus giving correct image matches over time.

2. OBLIQUE IMAGING

2.1 Oblique imaging instruments

Oblique camera systems can be categorised by geometric image formation, for example. The following list of systems is an adaptation from Petrie (2009, 2012), Meixner and Leberl (2010) and Rupnik et al. (2014). For some systems the end-product is a stitched virtual image of the separate camera heads. To enable as easy operability as possible with existing photogrammetric mission aircrafts, many oblique camera pods can be fitted to existing gyro-stabilised mounts.
Even though dedicated oblique camera systems are listed here, it should be remembered that single cameras starting from consumer-grade pocket-size cameras to professional-grade medium-format cameras are being used for oblique photography missions.

A fan structure camera system consists of several obliquely looking cameras with their optical axes on nearly one vertical plane, looking in different directions in a cross-track manner. Examples of this type are IGI Dual DigiCAM Oblique, DLR 3k and Visual Intelligence iOne-IMS. With this kind of camera, visibility to the side can be extended.

Another kind of camera system, known as a block structure camera, has several frame cameras combined in order to achieve larger ground coverage from a single imaging station. Examples of these are the Intergraph DMC (first generation), the Rolleimetric AIC x4, the IGI Quattro DigiCAM and the Urban Robotics PeARL six camera version. To be strict, some of these cameras cannot be categorised as real oblique cameras with regard to the optical axis deviation from the plumb line. However, some of them can be converted to become oblique cameras, e.g. the IGI Quattro DigiCAM to the IGI Quattro DigiCAM Oblique (Rupnik et al., 2014; IGI, 2015).

In the third kind of camera system, one camera shoots vertically and four or more cameras obliquely. This kind of system is often called the “Maltese Cross” system, because of the resulting image footprints. Examples are the Pictometry camera system (Kalinski; Höhle, 2008; Wang et al., 2008), the Track’Air/Lead’Air Chimera 400 MP Midas, the Microsoft UltraCam Osprey (Gruber and Walcher, 2013) and the Leica RCD30 Oblique. If adequate overlaps are maintained, the advantage of this kind of system is that each object in the ground can be seen from above and four or more oblique directions. At its best, a “Maltese Cross” system is complemented by viewing software, which handles the imagery related to each ground location.

In the fourth group the object to be imaged will be quickly scanned by area array sensors. This category includes stepping frame cameras, in which an area array rotates across the flying direction. One example of this is the VisionMap A3.

The fifth group consists of pushbroom cameras. Their main operating principle is similar to Leica’s ADS series, but with greater oblique imaging angles. One example is the Wehrli/Geosystem 3-OC with 45° angle separation between the vertical scan and the backward and forward scans. The pushbroom imaging geometry differs from the usual frame sensor model. In a pushbroom image, each scanline has its own exterior orientation values. In practice this kind of sensor is dependent on auxiliary location and orientation sensors.

Video cameras can be classified as a separate camera category. For years, even pocket-size cameras have been able to record Full HD video imagery. The trend is towards even better resolution and frame rates. One of the most potent video cameras today, with regards of resolution, is the Red.com Inc. Epic Dragon with 6K resolution. Rupnik and Jansa (2014) tested 30Hz dSLR video imagery in an industrial shape and motion reconstruction, concluding that the tested camera could be used as a measuring device and also finding that the lossy compression of the standard video format caused problems that could be handled with a Kalman Filter-based target motion model. If a video camera is under consideration for use in aerial photogrammetry, the operating principle of its shutter should be analysed.

As a rule of thumb, focal plane shutters (FPS) should not be used with frame sensor imaging from a moving platform, because the resulted image does not conform to the general pinhole model. If an FPS is used, the dynamics of the imaging process should be evaluated with regard to the total
frame exposure time and the flying parameters and – if necessary – to consider the possibility of using a time-dependent image formation model. There are cameras that have both an FPS and a central shutter (depending on the lens), e.g. the Phase One iXA-R (Phase One) and the Leica S (Leica).

One important feature of a modern photogrammetric camera is the forward motion compensation (FMC). The need for FMC can be evaluated when the intended flying speed, exposure time and imaging parameters are known. If FMC is needed in oblique image acquisition, and the imaging sensor is a frame sensor or a sideways-looking (i.e. left or right) pushbroom sensor, varying FMC should be used. Some of the oblique cameras in use nowadays do not include FMC or varying FMC.

With regard to camera installations in vertical photography, performed traditionally from manned twin-engine aeroplanes, camera ports in the aircraft floor are normally used. For smaller aeroplanes or helicopters, pods can also be attached under the wing, fuselage or bow, or on a skid. Such products, some of them incorporating sensors, are available from vendors such as SkyImd (SkyImd), GGS (AeroShift), Hood Tech Vision (Hood Tech Vision), DART Aerospace (DART Aerospace), Airborne Scientific (Airborne Scientific), Pictorvision (Pictorvision) and Gyron Systems International (Gyron).

2.2 Flying platforms and georeferencing equipment

The first, simplified categorisation of flying platforms can be made according to how the platform flies. There are aeroplanes, airships, gyrocopters and helicopters; in the following listing (Table 1), these are numbered from 1 to 4, respectively. There are also other ways of flying, such as hang gliding, paragliding, parachuting, gliding and kiting, which can be used in photogrammetry, but they are left out of this categorisation. In aeroplanes the lift originates from forward motion, causing compression under the wings. An airship, although quite rare in aerial photogrammetry, is a lighter-than-air platform that can move by its own power. A gyrocopter has an unpowered, auto-rotating rotor and a propeller for thrust. In a helicopter, lift and thrust are created by a rotor and the caused torque is compensated by counteracting force. For this study it is appropriate to use a subcategory according to payload in grams; here a three-step classification is used, namely A) under 500 grams, B) 500 – 20,000 grams, C) over 20,000 grams. The listed platforms are just examples of the myriad of total supply. Particular suitability for oblique imaging use has not been verified from the vendor. The payload of some of the presented examples is not user-replaceable. The choice of platform for a photogrammetric mission is also affected by the object area type, size and location, required accuracy, available funds, photogrammetric processing chain and the end-product. If manned platforms are an issue, the reasons for choosing a helicopter are the possibility of lower flying speeds and possibly an aviation authority permission to fly at lower heights than with a fixed wing aircraft; however, vibrations present with helicopters can mean that the pilot must fly at certain flying speeds instead of stationary hovering (Shortis and Ogley, 1988). More detail on the subject has been provided by Colomina and Molina (2014), Eisenbeiß (2009), Honkavaara et al. (2009) and Kemper (2012).

For added productivity and faster throughput times, modern aerial imaging systems are usually equipped with auxiliary georeferencing sensors. Georeferencing means tying the imagery to the chosen ground coordinate system. If the exterior orientation of the image is going to be solved by the measured and calibrated values of these georeferencing sensors, the approach is called direct georeferencing. There might be separate systems for the navigation of the platform. According to
Blázquez and Colomina (2012), the majority of (aerial) medium- to high-end mapping sensor systems have a geodetic grade GNSS (Global navigation satellite system) receiver and a tactical grade or better IMU (Inertial measurement unit). The GNSS/IMU system typically comprises a GNSS antenna in a place with good satellite visibility on the imaging aircraft, a GNSS receiver, an IMU, and a control and data recording unit (Beraldin et al., 2010). For decimetre-level accuracy, a differential GNSS measuring mode is needed; this can be implemented by a dedicated GNSS ground station or by using a national network of GNSS stations (Beraldin et al., 2010). Integration of GNSS and IMU is usually done so that the GNSS receiver is the main position sensor and the IMU the main orientation sensor (El-Sheimy, 2009). The GNSS gives in-motion calibration for the accelerometers and gyroscopes of the IMU (El-Sheimy, 2009). The IMU can be used for the detection and correction of cycle slips of the GNSS (El-Sheimy, 2009). Navigation information is gained by kinematic modelling of GNSS/IMU observations, usually by Kalman Filter (El-Sheimy, 2009). The exterior orientation of the camera must be traceable from the GNSS/IMU data; this includes the solution of temporal dependencies (Rehak et al., 2013; Grenzdörffer et al., 2008) and system calibration (Jacobsen, 2008; Madani, 2012; Tommaselli et al., 2013), and taking into account the related coordinate systems (Zhao et al., 2014; Bäumker and Heimes, 2001). It is of great importance to know the interior orientation of the camera if the direct georeferencing is used (Schenk, 1999).

Table 1: Examples of flying platforms categorised by operation principle and payload.

<table>
<thead>
<tr>
<th>Flying platform class</th>
<th>Examples</th>
</tr>
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<tbody>
<tr>
<td>1A C-Astral Bramor C4EYE (C-Astral), senseFly eBee (senseFly)</td>
<td></td>
</tr>
<tr>
<td>1B Falcon unmanned Falcon (Falcon Unmanned), FlyTech Solutions UAV FT-02 (FlyTech Solutions), MarcusUAV Zephyr2 UAV (MarcusUAV)</td>
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<tr>
<td>1C Beechcraft King Air C90GTx (Beechcraft), Cessna 206 Turbo Stationair (Cessna), Diamond Airborne Sensing DA42 MPP GUARDIAN (Diamond Airborne Sensing), Piaggio Aerospace Avanti EVO (Piaggio Aerospace), Vulcanair P68 Observer (Vulcanair)</td>
<td></td>
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<tr>
<td>2B Anabatic MZ6000 Outdoor (Anabatic), FKC-1 (Wei, 2009), Galaxy Blimp 30’ Outdoor Blimp (Galaxy Blimp), Nimbus Dirigibles N-700 (Nimbus Dirigibles)</td>
<td></td>
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<tr>
<td>2C GEFA-FLUG AS 105 GD (GEFA-FLUG), Zeppelin NT (Zeppelin NT)</td>
<td></td>
</tr>
<tr>
<td>3C AutoGyro Cavalon (AutoGyro), DiNelly Aerosystems eXoGyro (DiNelly Aerosystems), MMIST CQ10B (MMIST)</td>
<td></td>
</tr>
<tr>
<td>4A Airframe XM-6 Ti-QR (Aeronavics), Microdrones md4-200 (Microdrones)</td>
<td></td>
</tr>
<tr>
<td>4B Aibot X6 (Aibotix), Aeroscout Scout B1-100 UAV (Aeroscout), GOLIATH 8 (ArcTron 3D)</td>
<td></td>
</tr>
<tr>
<td>4C Airbus Helicopters H120 (Airbus Helicopters), Bell 206L4 (Bell Helicopter)</td>
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The orientation accuracy of an IMU is dependent mostly on the gyro drift rate (El-Sheimy, 2009). If the constant drift rate of the gyro is used for classification, four performance classes can be distinguished: strategic gyros (0.5 – 1.0 mdeg./h), navigation-grade gyros (2.0 – 15.0 mdeg./h), tactical gyros (100 – 10000 mdeg./h) and tow-accuracy gyros (100 – 10000 deg./h) (El-Sheimy, 2009). Technological development of IMUs is ongoing and, for example, there are location and orientation products using tactical gyros based on MEMS (microelectromechanical systems) technology (Novatel). For camera system development, many possibilities exist on the component market, such as Swift Navigation Piksi for GPS Real Time Kinematic receiver (Swift Navigation) and MEMS-based location and orientation devices (Applanix; iMAR Navigation; Xsens).
With oblique camera systems, which can be fitted to existing vertical camera mounts, the use of auxiliary georeferencing sensors is essentially similar to the vertical case. With handheld camera systems the use of GPS and IMU is also possible; Vallet (2007) described a Helimap System®, in which GPS, IMU, a 22 MP camera and a laser scanner are integrated in a handheld carbon-aluminium frame. Verhoeven et al. (2013) tested a Nikon DSLR camera-mounted GNSS/IMU for the purposes of archaeology. If low-cost and thus usually lower performance georeferencing equipment is used, the exterior orientation can often be improved in stereo-overlap situations by using traditional indirect photogrammetric methods.

Positioning services in Finland are available from the Finnish Geospatial Research Institute (FGI) and GeoTrim (GeoTrim), for example.

3. PROCESSING OBLIQUE IMAGES

Often the most important factor in accurate photogrammetric data capture is the camera calibration. In the calibration the principal distance, principal point offsets and lens distortions are determined (Remondino and Fraser, 2006; Kraus, 1993). There are different kinds of calibration types, starting from a laboratory calibration and ending up in an on-the-job calibration. In practice, the type of the camera to be calibrated and the aimed photogrammetric mission also affect the choice of calibration type. In the era of GNSS/IMU it has become popular to use photogrammetric test fields for system calibration (Tang, 2012; Cramer et al., 2010; Merchant et al., 2004; Grenzdörffer, 2008). Convergent imaging angles are needed in self-calibration to reduce the correlation between the interior and exterior orientation parameters (Brown, 1971; Walstra, 2006; Tommaselli et al., 2013). Thus, to-and-fro flying strips would be needed at minimum, when doing a calibration flight with fore- and aft-looking oblique camera systems.

Once the camera calibration has been resolved, the actual image orientation with regard to the chosen coordinate system can begin. If there is no direct georeferencing solution available, a common procedure is to point known coordinates from the imagery. An option would be to stay in an arbitrary coordinate system. If ground control points (GCPs) are needed in the orientation, one solution might be to use one of the commercial GCP providers, such as CompassData (CompassData). Another solution could be to rely on existing data that has already been georeferenced, i.e. some imagery with a cognisable sensor model, and height information. In seeking automation, ground control points can be handled as image chips, whose ground locations are known (Schowengerdt, 1997). There is software available for chip management, e.g. from PCI Geomatics (PCI Geomatics) and Spacemetric (Spacemetric). With oblique photographs the location of GCPs should be chosen from flat, texturised, minimum occlusion areas, such as uncultivated fields, side of the road or manmade surfacing. In order to allow statistical evaluation of the GCP, it should be visible and pointed from several oblique photographs.

However, the GCPs alone do not suffice when proceeding without the direct georeferencing solution into a bundle block adjustment. In the bundle block adjustment with the least squares method, the solution of nonlinear observation equations requires approximate exterior orientation values. It is more difficult to evaluate the values of unknown exterior orientation for an oblique photograph than it would be for a nadir photograph. The direct linear transformation (DLT) can be used for initial exterior orientation estimation for the frame camera sensor model. In computer vision it is quite common to use DLT, which is a direct conversion between image and ground coordinates. The great strength of DLT is that it does not need initial values for interior or exterior orientation values. In theory, the DLT solution needs six 3D GCPs, but in the author’s
own limited tests with oblique aerial images, the minimum amount of GCPs has been more than 20, if at least moderate result is required. The disadvantages of the DLT are slightly lower accuracy compared to a bundle block adjustment, and instability problems in the case of nearly coplanar GCPs (Mikhail et al., 2001; Karara, 1989).

In typical cases the majority of the points in bundle block adjustment are not GCPs, but tie points. Automatic tie point matching in the case of vertical imagery has been traditionally most often accomplished by using correlation. In the correlation the assumption of non-affinity is not ideal with oblique photographs, due to their nature. There are other possibilities, too. Remondino (2006) lists affine region detectors, namely Harris-affine, Hessian-affine, Maximally Stable Extremal Region (MSER), Salient Regions, Edge-Based Region (EBR) and Intensity extrema-Based Region (IBR). When regions extracted with these detectors are given descriptor values, matching can be done by comparing the Mahalanobis or Euclidean distance between the descriptor elements (Remondino, 2006). Morel and Yu (2006) introduced Affine-SIFT (ASIFT), which is a fully affine invariant detector and descriptor. Geniviva et al. (2014) presented a technique for automatic georeferencing of low-altitude, high-resolution oblique imagery based on the use of ASIFT algorithm. To detect blunders in candidate matches, random sample consensus (RANSAC) (Fischler and Bolles, 1981) could be used, for example.

After image orientation it is possible to measure 3D object coordinates by pointing corresponding image points in at least two images. It would be a considerable job to interactively seek all possible correspondences between overlapping images. Automatic surface modelling has been available for two decades and one of its recent developments is dense image matching. In dense matching, matches for each pixel in the reference image are sought from other images (Haala, 2013; Megyesi, 2009). Popular algorithms of dense matching are e.g. Semi-Global-Matching (SGM) (Hirschmüller, 2011) and DAISY (Tola et al., 2008). Sometimes it is necessary to align two height data sets with each other. Then algorithms like iterative closest point (ICP) can be used.

There is software intended for oblique aerial images. Examples of these include Ofek Aerial Photography’s Ofek MultiVision (Ofek; Grenzdörffer et al., 2008), Idan Computers’ Oblivision (Idan), ICAROS IPS (ICAROS, Shragai et al., 2011) and Airbus Defence & Space Street Factory (Airbus). Fugro Geospatial offers oblique image and software solution PanoramiX (Fugro). Blom offers BlomOBLIQUE imagery to be utilised by BlomWEB or BlomDESKTOP viewers (Blom). Pictometry offers oblique imagery, Electronic Field Study software and web-based solutions (Pictometry). Sanborn also has a web-based solution called Oblique Analyst (Sanborn). Geospan offers GEOVISTA API for image access from mapping systems (Geospan).

4. DEMONSTRATIONS

4.1 VisualSFM and SURE with Nikon D2X oblique images

Two pairs of slightly convergent oblique Nikon D2X image pairs with tilt angles of approximately 70.5° were oriented with eight and seven GCPs picked from the base map of the city of Helsinki. Flying heights of these images were between 140 and 180 metres above the average ground level (AGL). An orientation with a floating interior orientation was made with a computer vision software VisualSFM (Wu, 2013; Wu et al., 2011). VisualSFM uses SIFT features as a similarity measure.
The orientation data from the VisualSFM software was transferred to dense point cloud extraction software, SURE (Rothermel et al., 2012). SURE uses Semi-Global Matching (SGM) in the calculation. From the area an airborne laser scanning (ALS) point cloud was available and LAStools (LAStools) was used to extract the roof points from the data. A visualisation of the photogrammetric point clouds was created with software called CloudCompare (CloudCompare), picture 1. A cross-sectional comparison with the ALS data was performed with a FugroViewer software (FugroViewer), picture 2.

*Picture 1: Two stereopair point clouds near Malminkartano railway station. © Kaupunkimittausosasto, Helsinki.*

*Picture 2: Cross-section of a building. Yellow points from oblique images, blue points from ALS. © Kaupunkimittausosasto, Helsinki.*
4.2 VisualSFM, Socet Set and SURE with Nikon D3X oblique images

Structure-from-motion utilises high overlaps between images. In some cases the imagery of interest has not been collected with stereo compilation in mind or the imagery has been shot without adequate safety margins in stereo overlaps. The example images have been downloaded from the internet map service of the city of Vantaa (Vantaa) and their main purpose is for use in the general planning of Vantaa. In this study the imagery from 2011 from the Havukoski region was of interest, and the 12 images available from that year could not be oriented in one block with VisualSFM. The solution was to use all possible images from each year, namely 1996, 2001, 2004, 2007, 2011 and 2014, from the area. The images were photographed by Lentokuva Vallas (Vallas) and for the 2011 images the omega angle was about 47.9°, and flying height 1280 metres AGL. Some of the images in the internet map service were down-sampled versions and some were scanned film images. In total 80 images were put in VisualSFM and 52 of them could be handled in one block. Of those 52 images, 44 had GPS data inside the EXIF metadata, which was used to roughly orientate the block in the ECEF coordinate system, picture 3. An approximate coordinate transformation with the Coordinate Transformation Service (CoordTrans) of the Finnish Geospatial Research Institute (FGI) was used to proceed to the Finnish ETRS-TM35FIN/N2000 coordinate system. After this the data from 2011 was transferred to BAE Systems’ Socet Set software, in which automatic tie point calculation with blunder detection, observation of 27 manual GCPs referenced from the open data of the National Land Survey of Finland, and on-the-job-calibration were executed. The root of mean squared errors of the final bundle block adjustment were 0.89 pixels and 0.34 m (X), 0.65 m (Y), 0.54 m (Z) in the triangulation points.

The coordinates of the projection centres were brought back to VisualSFM, in which the 52-image block was re-oriented with these 12 image-capturing locations with 4.52 m root of mean squared error in the transformation. The image orientations of the images from 2011 were transferred to SURE, where point clouds were calculated for visualisation purposes, picture 4.

With the presented procedure it might be possible to get colour and structural information of the facades for the purpose of virtual city construction, for example. If simultaneous data is required, possible low stereo overlaps of the photographic missions can restrict comprehensive point cloud coverage; even in that case, any city models that already exist could be used in monoplotting.

mode by a single image ray intersection with the city model surface. To improve the VisualSFM software it would be useful to incorporate more complex lens distortion parameters. For high-accuracy work it could also be useful to take the earth curvature and atmospheric refraction into account, especially noting the oblique imaging geometry. Furthermore, it would be very useful in the VisualSFM software if the user could nominate different cameras for different groups of images. If further steps of the created point cloud were considered, some kind of point classification based on the city base map could be developed.

Further studies are needed to bring greater clarity to the success of using time-series in this test. Although there are large sideviews of buildings that are rather unchanged, the vegetation has grown during the years. One possibility may be that the downsampling of some of the imagery collection years actually helped in the solution. It is more obvious though that the automatic rejection of bad points is working as planned in the VisualSFM software.

Picture 4, point cloud of the Havukoski region, Vantaa. Original use of the oblique imagery is the general planning of Vantaa, © Copyright Vantaan kaupungin mittausosasto 2015, Nro 05/2015. Additional georeferencing data National Land Survey of Finland, NLS orthophotos 06/2015 and Elevation model 10 m 06/2015.

5. CONCLUSIONS

In the past, oblique aerial images were mainly used for presentation or interpretation purposes. In the last 15 years these images have been commonly and increasingly used for measuring purposes. There are different opportunities for their metrical use, ranging from smart single-image-based measuring techniques to utilising stereo-overlaps and different viewpoints to the object. Computer vision-originated procedures have had a great impact on the ease of use of these images. To boost the possibilities of oblique images even further, systematic stereo-overlapping image sets should be collected. This study shows that in structure-from-motion software, it is possible to enhance the oblique image orientation by using oblique image time-series. There is one existing technique that could revolutionise the scene in the near future, namely high-resolution oblique video imaging in a resolution range of between 4K and 8K. More studies are
needed in terms of intersection accuracy in order to fulfil possible uses in mapping. Applications requiring sideview visibility for objects can benefit the most from oblique images – these applications include city mapping and planning, virtual city reconstruction, structure inspections, emergency services, and military, forestry and coastal research.

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REFERENCES


Lyon, D., 1959. Basic metrical photogrammetry, Volume 1, John S. Swift Company, Missouri, USA.


