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Direct Georeferencing in Alpine Environments from a Helicopter

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Abstract

The paper describes the architecture of the helicopter-borne remote-sensing system Scan2Map developed at the Geodetic Engineering Laboratory of the Swiss Federal Institute of Technology at Lausanne (TOPO-EPFL). This system uses a combination of passive and active imaging (i.e., a digital camera and a laser scanner) and relies on direct georeferencing via GPS/INS for determining the exterior orientations (EO) of the image data. The system is well adapted to mountainous environments as it allows mapping also vertically oriented features (e.g., cliffs). The data flow of the system is briefly outlined and examples of applications in alpine environments are given with consideration of practical problems of data acquisition and processing.

The second focus is the transformation of the EOs obtained from direct georeferencing to national reference frames and their projection for mapping purposes. The required steps are explained and emphasis is put on the minimization of distortions arising from the curvature of the earth and the inevitable length distortion of the map projection. The correction of the vertical distortions is achieved by a specifically developed technique. The strengths of this approach are discussed and its limitations for applications in highly mountainous environments are analyzed.

KEY WORDS: High-accuracy mapping, direct georeferencing, national coordinates, height correction

1. Introduction

The majority of commercial mapping systems may be classified into either of two groups: (1) small-scale–large-area systems based on remote sensing from aircraft or satellites, and (2) large-scale–small-area systems that typically rely on geodetic surveying. There are missions where both of these approaches meet their limits – especially in mountainous environments: While the accuracy and/or level of detail provided by conventional remote-sensing systems becomes too poor, geodetic surveying turns laborious and uneconomic. The situation may be further complicated by short time-to-delivery requirements and limited accessibility to the area of interest.

The Scan2Map system overcomes these problems: Its accuracy and level of detail approximate those of geodetic surveying – notably without facing drawbacks of accessibility – and its mapping procedures resemble those of large-area systems. Thus, the advantages of both approaches are combined. The system involves a medium-resolution digital camera and a close-range laser scanner (Lidar). These sensors are complemented by GPS/INS navigation equipment for direct georeferencing of the image data. All devices are fixed to a common rigid senor mount. The uniqueness of Scan2Map is determined by the fact that the attachment of the sensor head to the airborne carrier is flexible. This allows the operator to manually pinpoint the sensor head towards the area of interest. Hence, an optimal image quality (in terms of visibility, geometrical accuracy, and contrast) is achieved – even when mapping very steep terrain. The flexibility is further increased by using a helicopter as carrier vehicle, allowing operations also in remote and otherwise inaccessible areas. Thanks to the use of direct georeferencing, there is no need to equip the area of interest with terrestrial control.

1.1. Structure of the paper

The paper is structured into two main parts: Section 2 provides more information on Scan2Map; it discusses several aspects of high-accuracy mapping of alpine environments and focuses on the architecture and some exemplary applications of the system. The transformation of image data obtained by direct georeferencing to national coordinates is treated in Sect. 3. The paper concludes with a brief summary and outlook (Sect. 4).

2. The Scan2Map system

The development of the system started in 1999, originally under the name Helimap. The targeted application was natural hazards mapping and management. From the very beginning, the requirements and development constraints included high spatial resolution, high mapping accuracy, portability of the equipment among different carrier vehicles, and low cost of the used sensors and components.

In the meantime, the range of applications has broadened substantially the system has made its way to the private industry. Further research with Scan2Map aims at the development of tools for analyzing the Lidar mapping quality on the fly.

2.1. High-quality mapping of alpine environments

The application niche of Scan2Map is characterized by high quality requirements. These are met due to the specific features of the system. The achieved resolution is given by the ground-sampling distance (≥ 4 cm) of the camera and the density of the laser range measurements (≤ 4 pt/m^2). The 3D mapping accuracy is typically 15 to 20 cm. To sustain this high quality level also in mountainous environments, several conditions must be met:

- The flight planning has to be done in a very detailed and careful manner. Thereby, a crucial issue is the visibility of the GPS satellites that may vary considerably over a day, especially in narrow valleys. The planned trajectory must be adhered to as close as possible during the actual flight for ensuring a complete coverage of the area of interest (Legat et al. 2006). The requirements on the planning will be lessened once the current developments of an online quality analysis are finished.
- When using a laser scanner, the quality of the remote-sensing data is influenced by the characteristics of the laser itself (e.g., wavelength, beam aperture, maximal range, processed echoes per laser ray) and also by the reflectance properties of the surfaces to be mapped. The latter depend on various effects (e.g., incident angles of the laser rays, surface roughness and type) which should be accounted for in the planning and/or online monitoring.
- The trajectory of the system needs to be estimated by kinematic GPS carrier-phase positioning followed by GPS/INS integration. Specific maneuvers are flown to guarantee a reliable estimation of the stochastic error processes affecting the output of the IMU sensors. The sensor head must be damped against vibrations exerted by the helicopter (Skaloud et al. 2006).
- Steep slopes may cause considerable difficulties to remote sensing. Especially nadir-pointing systems suffer from severe accuracy degradation in precipitous terrain due to poor incident angles. Often, relevant features of the terrain (e.g., cliffs) are not visible from above but only from a lateral view point. Scan2Map overcomes this problem as the operator may choose the obliquity

of the sensor head according to the inclination of the terrain, guaranteeing an optimal image- and ranging quality. A remaining difficulty of the data processing, however, is the modeling of vertical or overhanging surfaces in digital terrain models (DTM).

- The derived 3D scene usually needs to be transformed to some national geodetic datum and mapped by a map projection. In case of the Lidar, every measured point needs to be treated individually. In case of the camera, an approximate procedure may be adopted that requires transforming only the EO data obtained from GPS/INS. This apparently simple task poses some difficulties, especially in the height domain (Sect. 3).

2.2. System architecture

2.2.1. Components and data flow

The system has a modular architecture and involves off-the-shelf sensors and components:

- The camera features a high-quality lens system (focal length 35 mm) and a medium-resolution CCD array (approx. 5500 × 4000 pixels with 9 µm pixel size). The recording interval is 1.8 s between successive images.
- The Lidar has a scan rate of 10 kHz and a swath width of 60°. The rotating-mirror mechanism provides linear, unidirectional, and parallel scan lines with a programmable rate of up to 80 scan lines per second. The maximal range of the sensor is 650 m at 80% reflectance. The laser wavelength is well suited for scanning snow-covered surfaces.
- The onboard GPS equipment consists of a dual-frequency carrier-phase receiver/antenna showing favorable performance in kinematic surveying. The antenna is placed on top of the sensor head below the rotor.
- The IMU is a tactical-grade unit (gyro bias < 1°/hour). Its main responsibility is tracking the angular motions of the sensor head. Besides, it allows correcting inconsistencies and bridging gaps of the GPS data.

Figure 1: Scan2Map installed on an Alouette-III helicopter.

- The measurements of the Lidar, the GPS receiver, and the IMU are recorded on a laptop PC specifically designed for outdoor use. Finally, a moving-map display supports the pilot in navigating the helicopter along the planned flight lines.

The data-flow among the sensors and computers is based on Ethernet connections. The complete system is synchronized to GPS time. Further details on the system architecture can be found in Skaloud et al. (2006). A photo of the system during a flight is depicted in Fig. 1.

2.2.2. Advantages and restrictions

The unique architecture of Scan2Map provides a number of advantages: The sensor head has a low weight (approx.12 kg) that allows pointing it to the area of interest in an interactive way (by hand). The system can be operated both in nadir and oblique mode, the latter providing a side view from helicopter. The installation time is short (< 30 min), enabling a rapid deployment for missions on short notice. The carbon-aluminum frame of the sensor head guarantees rigid position- and attitude offsets (lever arms, boresight orientation) among all sensors. Thus, there is no need for recalibration. The flexibility of the system is further augmented by the availability of different inclinations of the GPS antenna mast (with calibrated lever arms for all variants), which allows covering a wide range of obliquities. The non-“intrusive” mapping method of the system and the use of direct georeferencing diminish the need for ground control in the mission area. There is no dependence on a certain helicopter type and no permanent installations are required in the craft. Finally, the system is a unique research tool. Contrary to (most) commercial systems, it allows an in-depth quality and integrity control and the development of novel applications.

Apart from these positive aspects, there are also some restrictions: The system operation is a relatively demanding task. It requires manual alignment of the sensor head by the operator, monitoring of the data quality by the controller, and the provision of navigation data for supporting the pilot. The range limitation of the Lidar and the resolution of the camera require a low flight height above terrain (200 m to 500 m). Thus, a detailed planning of the missions is crucial since navigation and targeting errors may cause coverage gaps. In mountainous environments, the situation is complicated by the GPS satellite visibility. The system is best suited for mapping areas of up to some 5 km².

2.3. Products and typical applications

In the technical sense, the product types available from Scan2Map include orthorectified images, digital surface models (DSM), and digital terrain models (DTM). These

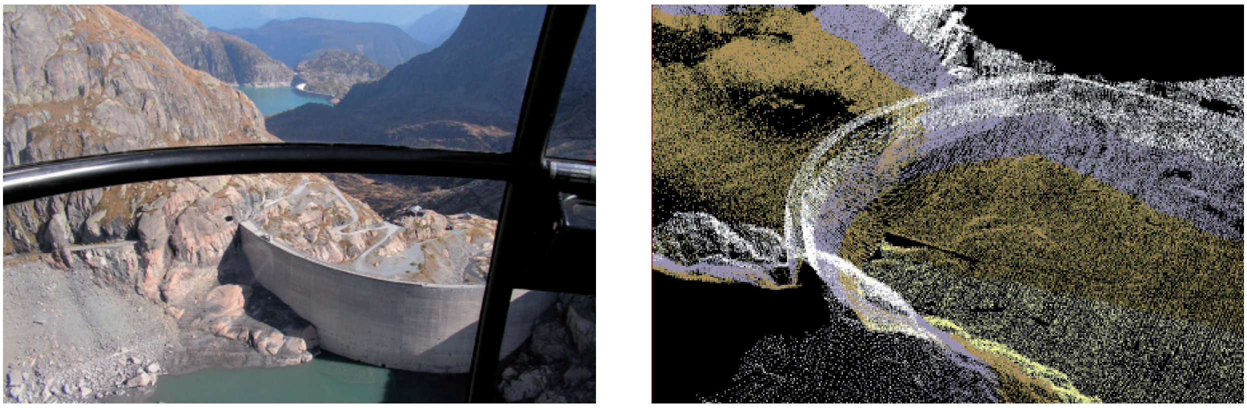

Figure 2: Project example at the water resort of Vieux-Emosson (Valais, CH). Photo (left) and laser point cloud (right).

types of products are needed for various different types of applications. The system is best suited for missions with high accuracy demands but limited geometrical dimensions. The majority of the Scan2Map missions are flown in difficult mountainous terrain. Typical applications include:

- Environmental monitoring and natural hazards management: Mapping and monitoring of landslides, erosion, mud-rock flows, flooding, glacier retreat/advancement, avalanches (volume determination), etc.
- Facility mapping: Surface (open-pit) mines, power plants, transport infrastructure, obstacle monitoring for airport facilities like runways, etc.
- Terrain-model analysis: Highly accurate mapping, detection of geomorphologic structures, slope and aspect analysis (even in case of steep terrain).
- Hydrologic modeling for flood-risk assessment.
- Forestry: Quantification and classification of bio mass.
- Corridor mapping: Line-based natural features (e.g., rivers, landslide areas) or man-made structures (traffic lines, power lines, etc).
- Urban planning, tourism, and GIS: 3D visualizations, fly-through simulations, regional or heritage promotion, spatial planning, etc.

Exemplary missions have already been performed for most of these application fields.

2.4. Project examples in alpine environments

Two exemplary missions shall demonstrate the performance of the system in alpine environments.

2.4.1. Sedimentation control of a high-mountain water resort

This mission was flown together with the private company UW&R SA in the canton Valais (south-western Switzerland) at the water resort of Vieux-Emosson (see http://www.emosson-lac.ch). The basin of the lake had been almost completely evacuated and the task was to determine a detailed DTM of the area to control its volume and the degree of sedimentation in the basin. The task was complicated by the steep cliffs surrounding the lake, see left-hand side of Fig. 2. The point cloud of the laser measurements after strip adjustment is shown on the right-hand side of Fig. 2. As can clearly be seen from these results the area is well covered, irrespective of the steepness of terrain and also of the dam.

2.4.2. Volume control in surface mining

The second example is based on a project performed together with Swissphoto AG in the canton Ticino (southern Switzerland) at an open-pit mine (http://www.salvisberg-gag.ch/bilder/steinbruch/iragna.htm). The mission area is a relatively narrow valley that is oriented almost in north-south direction. As is typical of such types of mines, the area of interest included a number of vertical surfaces (Fig. 3) which could only be treated thanks to the variable obliqueness of the sensor head of the Scan2Map system. The task was the determination of a high-accuracy DTM which also allowed a progress control of the mining work.

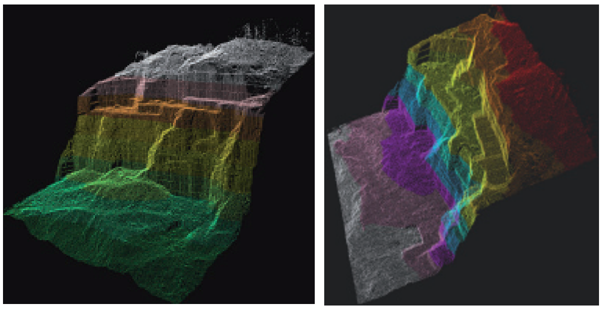

Figure 3: Project example at a surface mine (Ticino, CH). Perspective views from the east (left) and from above (right).

3. Direct georeferencing in national coordinates

This section marks the second focus of the paper. It is largely based on Legat (2006).

3.1. Problem description

The task of georeferencing is the determination of the EO parameters of an image sensor at the time of recording and the restitution of the scene from the image data. In case of passive sensors, the EO parameters may either be deduced indirectly from known ground control points (GCPs) or by measuring them directly by GPS/INS. Active sensors, in contrast, urge the use of direct georeferencing due to the sequential measurement principle and the motion of the carrier vehicle. Once the EOs of the images are known, the scene may be restituted from the image data. Thereby, the EOs are employed as transformation parameters for determining object points within the scene.

A frequent demand is the provision of remote-sensing products in national geodetic datums and using national map projections ("national coordinates"). In case of direct georeferencing, this requires some transformations to derive the desired final result. There are three options: (1) transformation of the complete scene after restitution; (2) transformation of "virtual" GCPs obtained from partial scene restitution; and (3) transformation of the EO parameters prior to restitution. The first method is well suited for active imaging. In contrast, the third one is the method of choice for passive imaging due to its practicability and low computational expense. At the same time, however, it is an approximation only, requiring two types of corrections: The first is the conventional earth-curvature correction that cancels the curvature-induced distortions in a relative sense (i.e., within the bundle of rays of an image). While this step is usually sufficient for indirect georeferencing, significant vertical distortions persist when applying it to direct georeferencing, even in case of flat terrain. These are caused by the inevitable length distortion of the map projection and the resulting difference in scale between planimetry and altimetry. The residual distortions can be substantially reduced, however, by applying a straightforward modification ("correction") of the image heights as will be shown below. Note that, although direct georeferencing is widely used in practice, the latter correction is often ignored and the respective distortions are wrongly attributed to GPS/INS errors or an inaccurate calibration of the focal length.

Subsequently, the required transformation and correction steps are discussed in more detail for passive imaging.

3.2. Geodetic datum transformation

The EO parameters need to be modified due to the transformation from the global geodetic datum (i.e., the reference frame in which the GPS satellite orbits are given) to the national datum. The datum change has two consequences: Firstly and trivially, the image positions must be transformed. Secondly and more subtly, the datum change also affects the spatial orientation of the local-level frame (more precisely, ellipsoidal tangential frame) used as reference for the attitude angles. This is due to the fact that the national geodetic datum is typically non-geocentric and that it uses an ellipsoid of revolution providing best fit to the geoid for the national territory (e.g., the Bessel ellipsoid in several European countries). Consequently, the attitude angles must be transformed too. The differences may take values of up to some 0.01°.

3.3. Map projection

Similar to the datum change, the consequence of the map projection is twofold: On the one hand, the transformed image position must be mapped. On the other hand, the varying convergence of meridians that comes with most conformal map projections (e.g., Transverse Mercator, Lambert conformal conical projection) must be accounted for. Although the latter varies across the area covered by an image, it is sufficient to use its value computed at the image position. In this way, the map projection frame is approximated discretely. Neglecting the convergence of meridians would render the attitude completely unacceptable as it takes values of up to several degrees.

3.4. Correction of geometrical distortions

The earth-curvature correction is a common tool in photogrammetry and it is described at length in the literature (Wang 1980). It is usually applied as a radial correction to the image coordinates for each individual image. Typically, the curvature-induced (relative) distortion within an image is well corrected by this approach. However, there is an important difference when applying it to indirect and direct georeferencing, respectively: In indirect georeferencing, the EO parameters of the images are unknown and need to be determined by relative and absolute orientation techniques. Thus, the bundle of (corrected) rays of each image is allowed to move "freely" to achieve consistency within the image block (via tie points), and the position and orientation of the block is fixed by GCPs. In contrast, the EOs are known in direct georeferencing, meaning that the bundles of image rays themselves are fixed in space. Together with the horizontal scale variation of the map projection, this causes the mentioned distortion of the heights in the restitution.

Following a mathematical derivation, it could be shown that the residual vertical distortions of the scene may be corrected by modifying the national height of each image as follows (Legat 2006):

$$h_{\text{image, corr}} = h_{\text{terrain}} + \tau \cdot (h_{\text{image, orig}} - h_{\text{terrain}}) \cdot (1 - h_{\text{terrain}} / R_{\text{earth}})$$

where

$h_{\text{image, corr}}$ ... modified (“corrected”) image height,

$h_{\text{image, orig}}$ ... original image height,

h_{terrain} ... average terrain height valid for the image,

R_{earth} ... mean radius of the earth,

τ ... local scale factor of the map projection.

It is worth mentioning that instead of changing the heights of the images, it is also possible to individually “correct” the focal length for each image. However, since the EO parameters need to be modified anyway when progressing to national coordinates, changing the height of the images is easily done as part of these transformations without altering the interior orientation of the camera.

The stated correction is not only valid for Scan2Map but generally applies to direct georeferencing of passive images. An impression of its numerical behavior is gained from Fig. 4. The plot demonstrates the influence of the average terrain height and refers to the outer zone of a projection strip when using the Transverse Mercator (i.e., τ = 1.00017). For a relative flight height of 1500 m, the correction yields values between +25 and –90 cm, depending on the average terrain height (between 0 and 5000 m). For an increased relative flight height of 3000 m, the correction amounts to between +50 and –185 cm. Clearly, these values are significant and the correction should not be ignored, especially for high-accuracy missions. Besides the correction itself, the figure also shows its dependence on the validity of the assumed average terrain height for the image. If the adopted value deviates ±100 m from the “true” terrain height, the residual errors are usually below ± 5 cm. Thus, the correction eliminates the dominant part of the vertical distortions. For greater height variations within single images, however, the residuals will grow too.

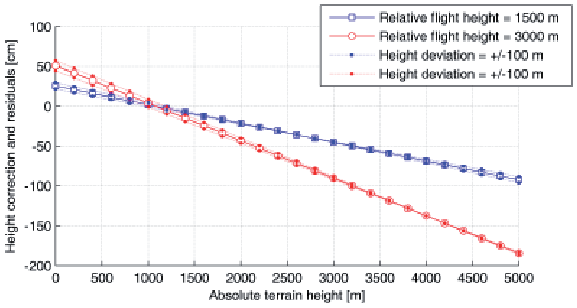

Figure 4: Required height correction at the outer border of the TM in function of the average terrain height for two relative flight heights together with the residuals for erroneous values of the average height. The relative flight height defines the slope of the correction function.

Note that the practical validity of this technique has been confirmed in several missions; one example is described in Legat and Skaloud (2006).

4. Summary and outlook

The paper has described the strengths of the Scan2Map system for high-accuracy mapping purposes in mountainous environments. Due to the approving quality of the remote-sensing data and its great flexibility, the system is ideally suited for applications like natural hazards monitoring. The continuing developments deal with the quality control of the mapping data on the fly.

In the second part, the height accuracy of direct georeferencing of photogrammetric images was discussed. A novel technique for treating the vertical distortions due to the curvature of the earth and the variable horizontal scale of map projections was described.

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