HELIMAP: DIGITAL IMAGERY/LIDAR HANDHELD AIRBORNE MAPPING SYSTEM FOR NATURAL HAZARD MONITORING

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Summary:

Natural hazard occurs over inaccessible and extremely dangerous areas where standard mapping techniques are a misfit. Moreover, the rapidity of the intervention is a crucial aspect when natural catastrophe strikes. In such event the standard photogrammetry or classical airborne Lidar are usually not flexible enough to become operational in few hours.
Originally developed for avalanche mapping, HELIMAP (www.helimap.com) is a portable mapping system for fast helicopter deployment. It integrates high accuracy navigation sensors (GPS/INS) with Airborne Laser Scanner (ALS) and 22Mpix digital (CCD) camera. The system can be mounted on most types of helicopters within minutes and offers autonomous 3D surface mapping (Digital terrain model-DTM and orthophoto) of any terrain (including snow) with decimetre-level accuracy up to 500m flying height above ground level. HELIMAP creation is a result of research carried out at the Swiss Federal Institute of Technology of Lausanne (EPFL) in the laboratories of Photogrammetry and Geodesy. The system's flying services and expertise are provided by a small private company (UWR SA).
The application field of the system spans from natural hazard mapping (avalanche mass balance, snow drift, debris flow volume, landslide, rockfalls, floods, etc.) to corridor applications (powerlines, rivers, roads, coast line, ect.) including large scale mapping over small areas.
The paper presents the system concept and characteristics, its different modes of operation and synthesis of practical experiences.

1. Introduction

1.1. Motivations

Due to the increasing pressure of the human activities in natural landscape, preventative measures against natural disasters require more and more studies and observations. In the cycle of integrated risk management, the steps of intervention and reconstruction following a disaster are studied, and then the phase of building or modifying is followed by implementation of prevention methods. Each of these phases attempts to reduce certain risks and impact of a natural catastrophe.
In this context, observation methods for phenomena and their impact on the land and infrastructure are essential to optimize certain processes and to make correct decisions. To detect and observe high risk areas, surveillance platforms collect continuously data. Land survey using GPS, photogrammetry and, more recently, laser and radar systems are the crucial tools helping in examining spatial aspect of the risk.
In the specific domain of avalanche monitoring, it is crucial to determine the mass of snow involved in the avalanche runoff and its spatial distribution. Then, the necessity to build a cartographic system that can be quickly deployed in the event of a catastrophe is born to respond to the needs of the Swiss Federal Institute for Snow and Avalanche Research (SLF).

1.2. Requirements

The designed system aims to fulfil the following requirements:

- Fast set-up and availability (minutes or hours)
- Relative independence from a particular helicopter
- Possibility to map near vertical (mountain faces) and horizontal (valley bottoms or flat areas) features during the same flight with uniform accuracy
- High relative and absolute mapping accuracy (<20cm)
- No assistance of ground control points

- Fast delivery time for DSM and orthophoto generation (few hours after flight)

1.3. History and evolution of Helimap system

The development of the system called HELIMAP started at EPFL in 1998 as a response to the requirements of SLF-Davos in mapping avalanches and snow transport [3]. The emphases were placed on high resolution and accuracy (10-15cm), low cost and system portability (i.e. independence from a carrier, [5]).
The initial sensor choice focused on high-quality portable photogrammetric camera that has been now replaced by high-resolution digital camera, with a similar quality to most commercial systems [4]. The technology for achieving direct georeferencing is the integration of carrier phase GPS receivers with inertial navigation system (INS). It permits tracking the 3D motion of the image sensor in space and time.
The sensor block was designed to be light and small enough to be hand-held by an operator. Therefore, the installation on the helicopter is very fast and a flying mission can be quickly executed over any type of terrain. Nevertheless, the process of creating DSM from photographs is relatively slow, particularly in steep slopes where automated procedures of restitution use to fail. The approach is therefore less suitable in applications where short time delivery of the results matters.
Except from other benefits listed in Table 1, integrating an airborne laser scanner (ALS) effectively eliminate this setback. The combination of GPS/INS and LiDAR data provide an almost automated generation of the DSM close to the real-time. Other advantages, such as the intensity observations, are independent of illuminations and are also of great value.

CCD/GPS/INS	**CCD/ALS/GPS/INS**
Autonomous	Automation of 3D map generation
Uniform accuracy	24 hours operation
Fine details, texture, ortho-photo	Intensity image (spectral characteristics)
Fast deployment	Quick mapping (day or hours)
Carrier (helicopter) independent	Uses custom integration and of-the-shelf sensors $\Rightarrow$ reasonable cost

Table 1: Benefits of laser scanner integration

As far as the cost is concerned, it is obvious that commercial system (>1000K USD) are not economically suitable for sporadic deployments over small areas. Moreover, the portability of the traditional laser scanner or airborne photogrammetric equipment between different carriers is limited because of specific demands (e.g., floor door) and the long set-up time. Hence, the maintenance cost of such designated system carrier is therefore another prohibiting factor for such type of application. Mandating a third-party service provider is not suitable due to the need of system availability on a short-time notice. Finally, the accuracy in mountains, where generally disasters occur, is poor for fixed systems due to unfavorable geometry ([1], [7]).
To maintain the benefits of LiDAR while keeping the total cost of sensor around 100K USD, a combination of a previously developed system [7] with a medium range (~500m) LiDAR has been undertaken.

The choice of a helicopter is justified by its ability to fly flexibly and close to the ground at low speed. This allows capturing photographs in large-scale and provides better flight line navigation. In the following, particularities of the system will be described together with an analysis of its performance.

2. System characteristics

As in its former versions ([5], [8]), the system integrates several sensors into a single block: a digital camera, an inertial measurement unit (IMU), a GPS antenna and an airborne laser scanner (LiDAR). The sensors are rigidly mounted on a light and compact carbon-aluminium frame. The block of sensors is handheld and allows large maneuverability while keeping constant relative orientation between them (Figure 1). Moreover, the system remains modular and, depending on the needs, units can be easily removed or re-assembled. Three main operational modes are possible:

1. Camera + GPS: 4.5 kg
2. Camera + GPS/IMU: 6kg
3. Camera + GPS/IMU + Lidar: 12 kg

Figure 1: The handheld block composed of all the devices: digital camera, laser scanner, GPS antenna and IMU

2.1. Imagery

The digital camera is composed of the Hasselblad H1 camera with available focal length of 35mm or 80mm that is attached to a digital back (Imacon Xpress 132C). The size of the CCD chip is 5448x4080 pixels with 9μm pixel size. The time mark of the shutter aperture is generated by a pulse, through the Xsync bus of the H1 camera that is time-registered in the GPS receiver via its event marker input. The choice of the lens was made based on its low distortion, a comparison of MTF curves and field tests. Images are stored on an external image bank that allow taking up to 850 shots each 2 seconds.

2.2. LiDAR

The Laser scanner unit is the Riegl LMS-Q240-60. The laser wavelength of 900um fits well measurements of natural targets and above all the snow covered surfaces. The maximum range is around 500m and the range resolution is 25mm. The scanner performs up to 80 scan lines per second at 10 kHz data rate. The rotating mirror induces a swath of 60° that corresponds well to the field of view of the digital camera that is 56° (with 35mm lens). Data are synchronized thanks to PPS pulse of the GPS receiver and a standard PC governs their storage through Ethernet.

2.3. Navigation devices for sensor's georeferencing

As with the use of sensors, the system remains modular in accommodation of navigation devices, namely the GPS receivers and the IMU. The system employs a Javad Legacy GD GPS receiver on board of the helicopter and additional GPS receivers on the ground as reference. In its most basic setup (CCD + GPS) the GPS data collection rate is set to 5 Hz, which is sufficient sampling rate for the dynamic of a helicopter. This rate is reduced to 1 Hz or less when IMU is employed.

The IMU is tactical-grade strapdown inertial system (LN-200 A1) with 400Hz measurement rate. The IMU data are synchronized through small custom interface ([9]) and sent via Ethernet link to a standard portable PC as schematically depicted in Figure 2. Again, modularity was in the design priorities here, and then the GPS receivers as well as the PC are easily interchangeable in case of hardware failure. The recorded IMU data are used in a post-mission integration with the differential carrier phase GPS data via a Kalman Filter employing 25 to 30 states.

2.4. Helicopter Mount

The helicopter mount (Figure 3) is independent from its carrier, which has several advantages. First of all, the installation time takes only few minutes. Second, changing carriers does not require re-calibration of the sensors. Third, its flexible handling allows maintaining optimal geometry of the sensors in steep and flat terrains for the benefit of higher mapping accuracy. Finally, most of the propeller-induced vibrations are dampened when the operator holds the system and activates the imaging sensors [5]. An additional steel holder can be added to the exterior of the helicopter to support the system during approach flights.

2.5. Flight management

The system is designed to map smaller areas at large-scale, which permits a simple but efficient flight management concept. The system operator drives image overlap and shots timing whereas the navigator/pilot steers along the flight line. The flight-line navigation uses the display of a rugged PC running PenMap™ software accepting the NMEA/GGA message sent by the GPS receiver. Then, navigation accuracy better than 20m is guaranteed in planimetry while a barometric altimeter assures the control of the height. The display of the LiDAR control software was modified and thus permits to check in real-time the mean range of the measurement, the swath covered, the velocity of the helicopter, the synchronization of the LIDAR data and the number of event marks induced by the picture shots.

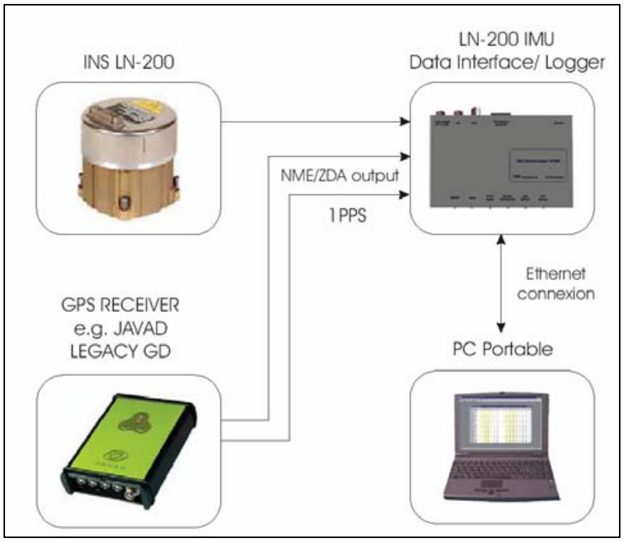


Figure 2: Data flow and synchronization for the IMU/GPS units.

Figure 3: The system in action with Alouette III helicopter. The holder for supporting the system weight during transition flights is located under operator's right leg.

3. System calibration steps

The system calibration can be divided into a few basic steps:

- Lever arm calibration: finding the linear offsets between each measurement unit
- Boresight calibration: determining the angular offsets between the IMU and the sensors due to mounting
- Interior calibration: finding or re-fining parameters related to sensors' interior orientation (Lidar, camera).

All the calibration procedures inherent to the lever arms, Interior orientation and camera-IMU boresight have already been described in details ([6], [8]).
To resume those steps, the lever arm calibration is made in laboratory, using calibration polygon for the camera parameters and tacheometric measurement of the different sensors origin. The resulting accuracy is better than 1 cm for each distance. This step is performed one time for all.
The boresight between camera and IMU is determined on flight using a new approach developed by Skaloud and Schaer [6]. Under the crucial condition that the IMU is accurately aligned [5], a precision better than 0.005° in roll and pitch and 0.01° in yaw has been achieved on several test flights.
The interior orientation of the camera is regularly checked in flight over small signalized areas.

The last calibration step is the boresight between the laser and the IMU. An on-flight calibration is performed according to the following procedure:

- Several light lines are flown at different altitude and in opposite and cross directions over a well signalised area with plane surfaces (e.g. roof, football field).
- Determination of the several points of the plane surfaces (GPS) to derive the plane equation.
- Performing aerial triangulation using GPS and GCPs and stereoplotting of the plane surfaces and then derive also plane equation to check the quality of the bundle adjustment
- Computing the laser data assuming the boresight is null and extracting the points corresponding to the plane surfaces

- Minimizing by least square adjustment the discrepancies between plane equation and laser points using the boresight angles as unknown (equation 1, 2 and 3).

The following equation describes the relation between object coordinates of a point P and Laser/IMU/GPS measurements

$$\mathbf{X}_P^E = \mathbf{X}_{GPS}^E + \mathbf{R}_{IMU}^E \cdot \mathbf{R}_{ALS}^{IMU} \cdot \left[\mathbf{r}_{GPS-ALS}^{ALS} + \mathbf{r}_{ALS-P}^{ALS}\right] \tag{1}$$

where

$\mathbf{X}_P^E$: coordinates of the point P in the object frame E

$\mathbf{X}_{GPS}^E$: coordinates of the GPS antenna in the object frame E

$\mathbf{R}_{IMU}^E$: Rotation matrix from IMU frame to object frame (IMU measurements)

$\mathbf{R}_{ALS}^{IMU}$: Boresight matrix (can be expressed as a combination of a mounting matrix and small values boresight angles rotation matrix: $\begin{bmatrix} 1 & e_z & -e_y \\ -e_z & 1 & e_x \\ e_y & -e_x & 1 \end{bmatrix} \cdot \mathbf{M}$ with e_x, e_y, e_z the boresight angles.

$\mathbf{r}_{GPS-ALS}^{ALS}$: vector of the lever arm between GPS antenna and laser origin

$\mathbf{r}_{ALS-P}^{ALS}$: vector of the laser beam of the point P

For each point P that should belong to the plane, the minimal distance to the reference plane is given by:

$$\delta_P = \frac{ax + by + cz + d}{\sqrt{a^2 + b^2 + c^2}} \tag{2}$$

where a, b, c and d are the coefficient of the plan equation a*x*+b*y*+cz+d = 0
Thus, equation 2 can be expressed as a function of e_x, e_y, e_z :

$$\delta_P(e_x, e_y, e_z) = \frac{k_{1p}e_x + k_{2p}e_y + k_{3p}e_z + k_{4p}}{\sqrt{a^2 + b^2 + c^2}} \tag{3}$$

Because of the limited navigation accuracy during the calibration flight, it has not yet been possible to fully evaluate the performance of this calibration procedure above the system noise-level. Also, employment of the solution offered by TerraMatch™ software indicated that the boresight angles were smaller than the IMU data noise level and the results did not appear significant. The recent realization of a new experiment is still under evaluation.

4. System performance

The HELIMAP system has undergone several years of experience in the first two modes of operation (Section 2). Its quality is appreciated in frequent flying missions related to natural hazards applications. The functionality and benefits of adding ALS became apparent during a feasibility test that was realized in February 2004. Preliminary results are presented in the following.

4.1. Imagery

Changing from analogue to digital camera [7] was supported by field and laboratory experiments. Comparisons between the digital images and the digitized films revealed that digital sensors provide sharper and less noisy images than a film-based imagery as shown in Table 2.

The higher image quality of a digital camera allows reducing the scale two times with respect to analogue camera without losing the details. This fact partially compensates for the smaller format of the CCD sensor, which requires taking significantly more photos to cover the same area.

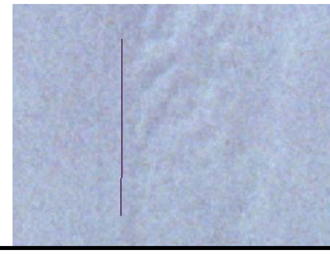
	Digital (1:7000)	Digitized Film (1:4000)
Transition B/W	½ pixel 1.5gsv	3-4 pixels 6gsv
Noise (1σ)		

Table 2: Comparison of digital/analogue photos in terms of sharpness and noise (gsv = grey scale value).

4.2. Mapping Accuracy

Photogrammetric accuracy

The following evaluation will focus on the system absolute accuracy at discrete points. A test field divided in two areas of about 25 and 12 GCPs, respectively, will serve the purpose. The scale of the images that were taken over this test field varies from 1:9000 to 1:11000 and the accuracy of ground control points is at 2cm level. As some GCPs are not specially signalized, the measurement of their image coordinates may introduce additional error from 2μm to 6μm (i.e. 2-7cm in the object space).

Method		Constrains GCP	Block	RMS at GCPs [cm] application field σ_0 [μ]	X,Y	Z
AT		●	●	2	4	4
AT-GPS			●	2	9	10
GPS	I: 1 step			10	12	15
/	II: 2 step no corr.			9	15	17
INS	III: 2 step + **time corr.**			**7**	**10**	**14**

Table 3: Comparison of mapping accuracy between different approaches to EO determination with an indication of operational constraints.

The indirect (AT, AT/GPS) and direct (GPS/INS) approaches to photogrammetric mapping are compared in Table 3 in terms of empirically estimated accuracy. The direct georeferencing by GPS/INS is further evaluated with respect to the different methods of boresight estimation as presented in the previous section. It is apparent that accounting for temporal correlation in IMU data during boresight estimate (Table 3) reduces image residuals and improves accuracy of object coordinates. Although the RMS values for the direct method are slightly higher than those for the indirect approach, the demand for providing 20cm-level mapping accuracy or better is fulfilled. The benefits of direct georeferencing are, however, numerous, as it avoids many difficulties that arise when performing automated AT in mountainous terrain. Adopting this method also considerably increases the operational flexibility needed in natural disaster mapping. The AT-GPS approach remains an interesting option for areas where GCP's are difficult to implement, but the relief and texture allows successful automation of tie point measurements procedure.

LiDAR accuracy

The principal factor affecting the accuracy of the LiDAR measurements remains the precision of the navigation components (GPS/INS) and the determination of the boresight angles. As mentioned in the Section 3, the IMU data of February 2004 were affected by the weak alignment due to limited helicopter dynamic and did not permit to obtain the orientation angles with predicted accuracy better than 0.08°. Nevertheless, a rough estimation of the global accuracy of the system was studied through:

- Comparison between control surface measured by GPS and stereoplotting without any filtering of the LiDAR data.
- Inner precision evaluation by comparing the flight lines

A comparison between ground measurement, photogrammetric plotting and laser data, assuming that the boresight was zero, revealed a standard deviation of the residuals of 5 to 10cm over flat terrain. The figure 4 illustrates the variation of the laser data from the control surface. The small systematic error (~0.05cm) can be tied to boresight misalignment but maybe also due to GPS precision. The same evaluation is still under process for steeper slopes.

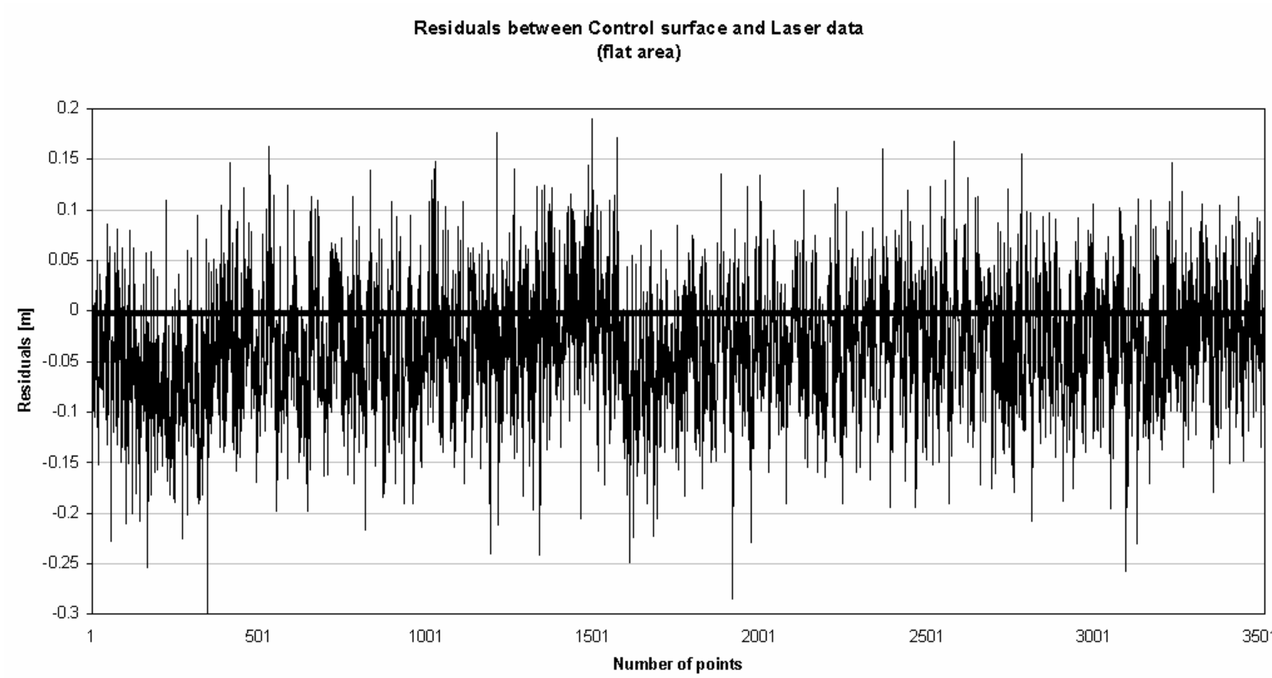


Figure 4: Residuals between control surface and laser data (flat area). Flight height is 260m above ground.

The inner accuracy of the LiDAR measurements was achieved by comparing the surface of several flight lines. No pre-filtering of the data was performed.
The test revealed that a noise level of 5-7cm that could be drastically reduced by filtering or by computing key-points. The effect of such filtering is still under evaluation.

4.3. Cost considerations

The cost of the mapping system is an important and sometimes a decisive factor for its adoption. Apart from counting the value of hardware (Table 4), the cost evaluation should also consider the amount of work related to each mode of system operations (Table 5).

Equipment	Cost [€]
Digital Camera	25’000
GPS receivers	10’000
IMU (LN-200 A1)	15’000
Lidar (LMS-Q140i-60)	50’000
IMU interface	2’000
Frame	2’000
Computer	2’000
TOTAL HARDWARE COST:	106’000

Table 4: System equipment cost.

As can be seen from Table 5, the image orientation and DTM generation can rarely be automated in ‘non-standard’ scenarios involving steep terrain. As these tasks are time consuming, their liberation by LiDAR well justifies the supplementary hardware cost of USD 35K. The total equipment costs amount to approximately USD 100'000. This is almost an order of magnitude lower than most of the turn-key commercial systems. In other words, the cost of a development leading to a modular fully digital large scale mapping system of decimeter accuracy has been justified.

OPERATION MODES	GEOREFERENCING			PRODUCTS	
	GCP	Tie points	Navigation	DTM	Ortho-photo
AT	● M	● M	-	● M	● A
AT-GPS	-	● M	● A	● M	● A
Direct (CCD/GPS/IMU)	-	-	● A	● M	● A
CCD/GPS/IMU/ALS	-	-	● A	● A	● A

Table 5: Comparison of processing tasks (M: manual, A: automated) for different modes of system operation.

5. Application fields

Although Helimap was initially designed for natural hazard mapping, its range of application widened to any large scale mapping while the area does not exceed 500-800 ha (fig. 5).

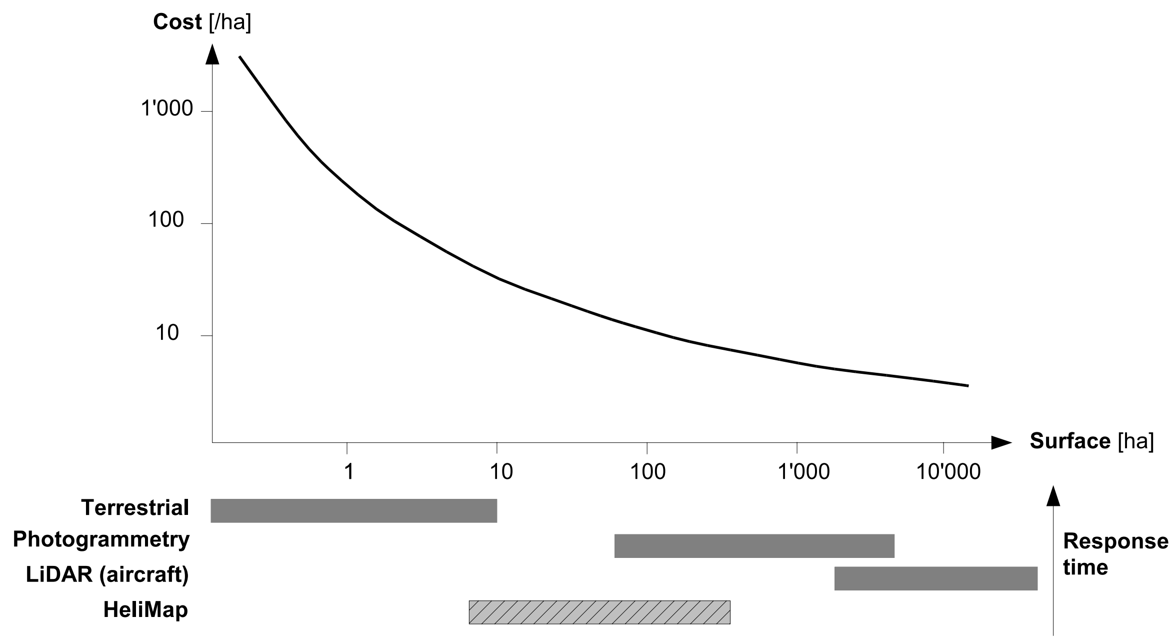


Figure 5: The position of HeliMap system among other mapping techniques in terms of cost, surface and response time.

The main applications where Helimap is involved are (figure 6):

- Natural hazard mapping (avalanche, landslide, flood, debris flow, glaciology, volcanoes, forestry, etc.).
- Inaccessible or dangerous area (mountains, cliffs, steep slopes, post-conflict local mapping, etc.)
- Corridor mapping (roads, powerlines, railroad, coast, rivers, etc.)
- Any large scale mapping (3D model, cities, recreation areas, etc.)

The integration of the LiDAR suppressed the main weak point of the system in terms of results delivery delay.

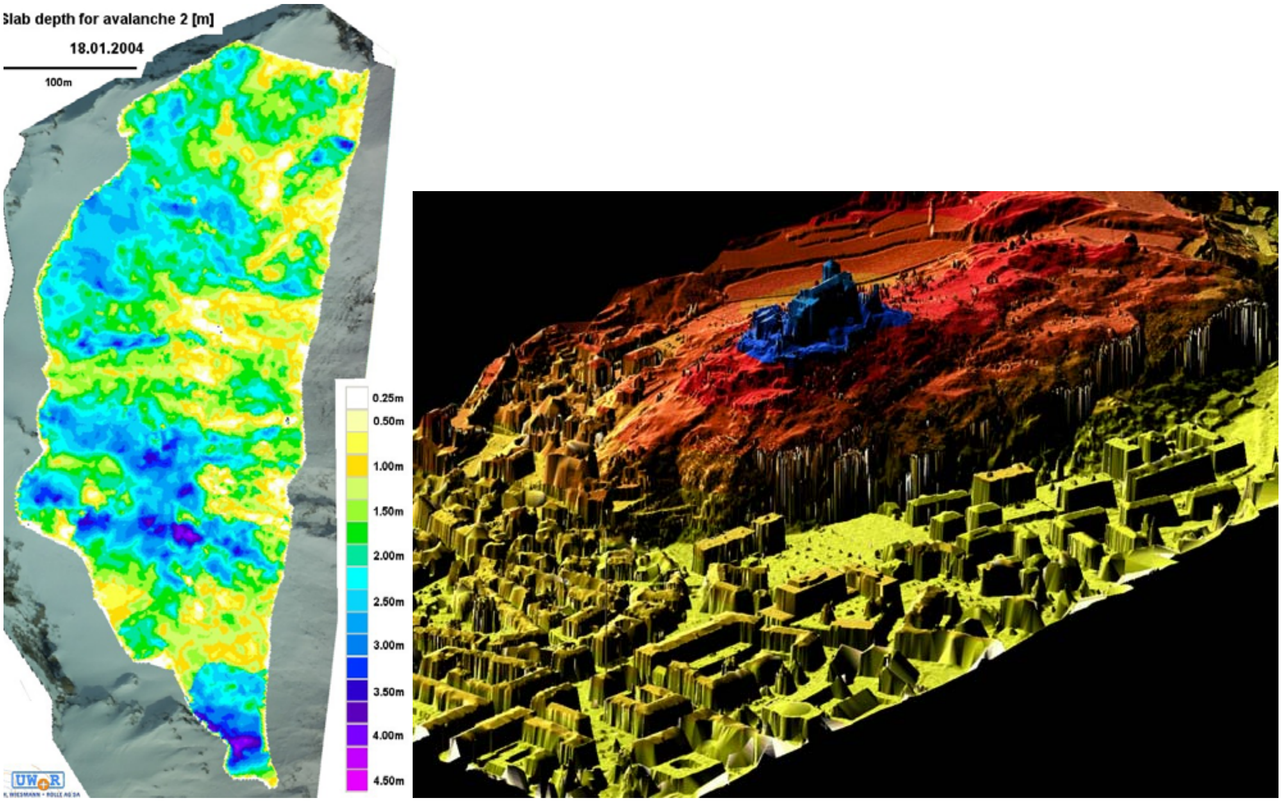


Fig 6: *Left*: Snow height mapping for avalanche monitoring. The map shows the height of a snow slab triggered for avalanche study. *Right*: 3D model of the city of Sion and its castle (Switzerland).

6. Conclusion and perspectives

The development of a dedicated airborne mapping system (HeliMap) was initiated as a response to the country's needs for natural risk management and monitoring. The objective was to design a self-consistent system, easily deployable on a helicopter that can provide digital surface mapping of an area of interest:

- With a high precision (0.2m),
- With a high resolution (<1m²),
- Shortly after the flying mission (few hours).

The evolution of the system followed the emergent technologies used in modern mapping and remote sensing. After replacing the analogue camera with a CCD sensor to increase the image quality, an airborne laser scanner was added to drop the need for photogrammetric stereoplotting.

At the same time few approaches were investigated in the direct georeferencing, especially with respect to boresight calibration (IMU/LiDAR/CCD). The calibration model has been established. Nevertheless, the limited quality of the navigation data during the first test flight with LiDAR did not permit to fully evaluate its potential. A second test flight should complete this information .

The mapping experience with the system in CCD/GPS/IMU mode has proven its unique performance in terms of flexibility, cost and accuracy (<20cm). To improve the production time and hopefully fully automate the mapping process, a LiDAR has been integrated to the system. A preliminary evaluation of the accuracy provides interesting results. However, the complete evaluation of the new ALS/CCD/GPS/IMU operation is still yet to be finalized.

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