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INTEGRATED THREE-DIMENSIONAL LASER SCANNING AND AUTONOMOUS DRONE SURFACE-HOTOGRAMMETRY AT GOMANTONG CAVES, SABAH, MALAYSIA

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The famous "bird's nest caves" of Gomantong Hill, Sabah, are believed to have been extensively modified by zoogenic erosion. We have mapped the caves and the overlying land surface with unprecedented precision, by integrating aerial photogrammetry using an autonomous drone, three-dimensional cave laser scanning at millimeter resolution, differentially-corrected geodetic GPS, and conventional compass-based cave surveying techniques. These data provide exceptional insights into the interplay of biology and geomorphology, with direct benefits for sustainable management planning.

1. Introduction

In recent years, the increasing availability and decreasing size of three-dimensional laser scanners, sometimes called "terrestrial LiDAR" (T-LiDAR, or TLS) scanners, has spawned numerous examples of their use underground. Early examples include Marais (2005), and Fryer et al. (2005). Until recently, these projects have been largely of a proof-of-principle, or of a simple imaging nature, and have been generally limited to geometrically simple cave passage morphologies (e.g., Gonzalez-Aguilera et al. 2009). Current trends are towards the use of 3D laser scanning technology to address specific scientific questions, such as passage stability analyses (Lyons-Baral 2012), bat counting (Azmy et al. 2012) and ice volume studies (Milius and Petters 2012, Buchroithner et al. 2011, 2012; Petters et al. 2011). There has also been an increase in the scanning of progressively more technically difficult and complex caves (e.g., Buchroithner and Gaisecker 2009; Addison 2010). Here we present a study that integrates high-resolution 3D scanning of complex cave morphologies with high-precision photogrammetric modeling of land surface topography, with the goal of investigating the speleogenesis of distinctive large cave passages in tropical karst structures.

2. Methods

Simud Hitam and Simud Puteh are two large volume limestone caves known for their culturally and historically important bird's nest harvesting industry (e.g., Burder 1961; Wilford 1964; Price 1996; Lim and Cranbrook 2002) that are located in Gomantong Hill, Sabah, Malaysia (5.52986° N, 118.07164° E). The best publicly available digital elevation model data for Gomantong Hill is the 30 m resolution ASTER dataset (http://asterweb.jpl.nasa.gov/gdem.asp), which is two orders of magnitude too coarse for our purposes. Hence, we obtained high-resolution imagery over the site using a Gatewing X100 autonomous drone (http://www.gatewing.com/X100), an aerial vehicle with a wingspan of 100 cm and thus well-suited to transport to remote locations. The vehicle was flown at 400 m elevation, obtaining a dataset of 240 overlapping images with ~6 cm geometric resolution and covering 2.1 km^2 (Figure 1a). Control points were taken using a Trimble GeoXH 600 geodetic GPS receiver (which provided ~25 cm real-time precision under tropical forest canopy) and a Trimble NetR9 base station providing centimeter-level post-processing precision. Photogrammetric processing of the Gatewing imagery was

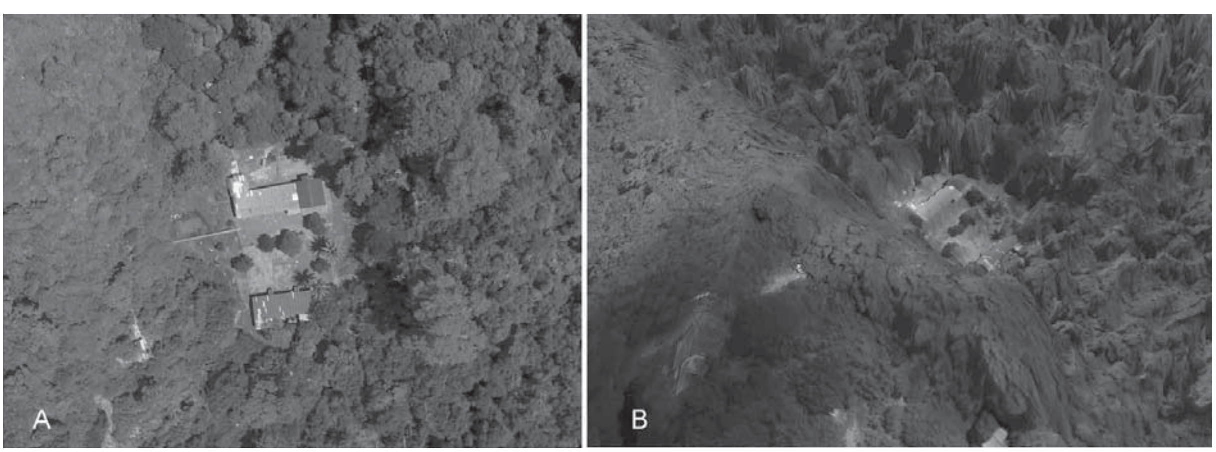

Figure 1 (a) Gatewing imagery, nest collectors longhouse, Gomantong. (b) Gatewing imagery draped over reconstructed digital surface model, Gomantong Hill.

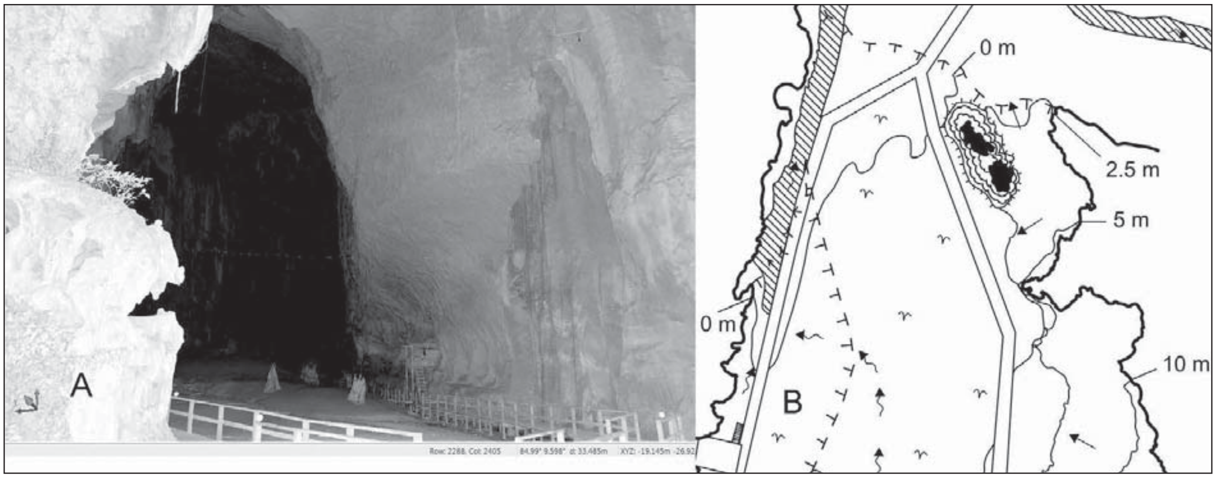

Figure 2. (a) 3D point cloud in FaroScan, Simud Hitam entrance. (b) Plan of Simud Hitam based on LiDAR data, with centimeter-precision wall detail.

performed using "Stretchout" software (http://www.gatewing.com/stretchout), employing a mean of 3080 keypoint observations per image. The final digital surface model has x/y and z axis means of 0.198 ±0.12, and 0.109 ±0.08 and one sigma errors of 1.095 ±1.07 meters respectively (Figure 1b).

Three-dimensional cave scanning was performed using a FARO Focus3D instrument, generally at ¼ resolution mode (= 244,000 points/seconds, yielding x-y point cloud spacing of 12.5 mm, ±2 mm ranging error, at typical wall/roof distances of 20 m), with additional scans at full resolution (x-y-z point cloud spacing of 3.1 mm, ±2 mm at 20 m) where required for specific geomorphological analyses. Data processing was done with FaroScene software (Figure 2a).

The cave was also surveyed using conventional compass-based survey techniques with a SuuntoKB-14/360R compass, a Bosch DNM6 digital inclinometer custom-fitted with a laser pointer (±0.1 degree precision), and a Leica Disto.

Lite 5 laser rangefinder (±3 mm precision). Data were processed in COMPASS software, version 5.06 (http://fountainware.com/compass/). Passage walls were drawn by integrating a "slice" of the T-LiDAR data with the COMPASS baseline, providing an exceptional degree of wall detail (Figure 2b).

3. Results

Survey statistics for the two caves appear in Table 1. A total of 69 scans, comprising in excess of 5 billion data points, were obtained in the lower "Black Cave" (Simud Hitam), and merged and processed with Faro Scene 5.0 software (http://www.faro.com/focus/us/software). A further 55 scans were made in the upper "White Cave", Simud Puteh.

4. Discussion and Conclusions

A standard statistic produced by COMPASS cave survey processing software is "volume density", a rough estimate of the proportion of the rectangular block bounded by the x, y, and z extremities of the cave occupied by cave passage (the later generally derived from simple polygon estimates of cave volume).

Table 1. Survey statistics for the Gomantong Caves.

	Simud Hitam	Simud Puteh
Surface length (m)	190.5	388.7
Surface width (m)	230.2	537.4
Depth (m)	88	188.5
Enclosed rock volume (m^3)	3,498,547	39,379,506
Surface area (m^2)	43,842	208,884
cave floor area (m^2)	15,549	38,640
Cave volume (m^3)	1,083,664	963,000

Volume density for Simud Hitam is 30.9 %, and for Simud Puteh it is 2.4 %. The volume density of Simud Hitam (the Lower Cave) is much greater than would be anticipated by modern hydrological conditions. It is believed that it is the result of extensive biogenic erosion driven by physiological processes associated with the large bat and swift populations, and by guano decomposition (Lundberg and McFarlane, 2012). These processes generate distinctive small-to-medium scale geomorphological features which we have termed "apse flutes". The integration of terrestrial LiDAR scanning with conventional cave cartography has enabled us to generate cave plans with centimeter precision and which allow these biogenic features to be quantified for the first time. Simud Puteh has been much less modified by these processes, apparently because of its proportionally smaller bat and swift population sizes. Thus, Simud Puteh better preserves the passage morphologies of the original "hydrological" speleogenetic processes.

Cave T-LiDAR scanning provides additional data that can be of value in biological inventory and management studies. Azmy et al. (2012) have shown that T-LiDAR can resolve individual bats on cave roofs with sufficient resolution to distinguish species identifications in some cases. At Gomantong, we have shown that T-LiDARdat can easily discriminate swift nests on cave roofs, and we are currently developing automated counting algorithms based on nest versus limestone laser reflectance values. This technique may prove to be useful in long-term swift population monitoring, which is a prerequisite to effective management of a sustainable nest collection industry.

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