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Counting in the dark: Non-intrusive laser scanning for population counting and identifying roosting bats

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Population surveys and species recognition for roosting bats are either based on capture, sight or optical-mechanical count methods. However, these methods are intrusive, are tedious and, at best, provide only statistical estimations. Here, we demonstrated the successful use of a terrestrial Light Detection and Ranging (LIDAR) laser scanner for remotely identifying and determining the exact population of roosting bats in caves. LIDAR accurately captured the 3D features of the roosting bats and their spatial distribution patterns in minimal light. The high-resolution model of the cave enabled an exact count of the visibly differentiated *Hipposideros larvatus* and their roosting pattern within the 3D topology of the cave. We anticipate that the development of LIDAR will open up new research possibilities by allowing researchers to study roosting behaviour within the topographical context of a cave's internal surface, thus facilitating rigorous quantitative characterisations of cave roosting behaviour.

Ecological studies of biospeleology and chiropteran studies have routinely used many established, non-intrusive methods to determine species' populations. Examples of methods utilised in chiropteran population studies include acoustic bat detectors, visual observations, infrared cameras, thermal imagers and radar systems. However, these methods have many major limitations. Acoustic bat detectors are affected by the absorption of ultrasound waves in the air and are limited to a range of less than 25 m. Furthermore, the effectiveness of such detectors decreases in humid and misty conditions. Visual observations are only possible in daylight or in crepuscular conditions, such as at dusk or dawn. Emergence counts are made visually at dusk by using a bat detector to confirm a species. Night vision devices are inaccurate in lower light conditions because of a lag time that fails to provide suitable images of flying bats. Infrared (IR) cameras and camcorders are used with an IR illuminator to observe bat emergences and bat behaviour inside and outside roosts, but this method is tedious and time consuming. Infrared beam devices usually require a strong power source, and they are usually not mobile. Thermal imagers are limited in range and are unable to identify bats because of their small size and emissions. Passive infrared sensors have a response speed of approximately one tenth of one second and will not normally detect a small fast mammal such as a bat. Radar has been used to detect bats beyond the acoustic limit, but the equipment and man-hours that are needed to operate radar are expensive.

Historically, censusing bats in caves involves a direct roost count of single individuals or small clusters, while larger clusters are estimated by multiplying the number of bats in the counted area by the total area needed to cover the entire roost. Traditional counting methods, such as emergence counts, dispersal counts and disturbance counts, are limited to daylight or crepuscular conditions, such as dusk or dawn, and are often conducted with a bat detector for species confirmation. Indirect estimation at cave entrances typically utilises emergence counts, harp traps and mist nets[1].

Roosting studies are important because they characterise the bat species and provide population estimates that are needed to make conservation and management decisions. Roosting activities fulfil thermoregulatory requirements, allow cooperative breeding and lower individual predation risk. Reproductive bats have thermoregulatory preferences that lead to differences in roosting site selections. Among reproductive females, lactating individuals may select relatively warm roosts to avoid torpor, whereas pregnant bats may facilitate torpor by choosing cooler roosts. These potential preferences lead to the hypothesis that, within colonies, the roost sharing and roost-switching patterns of non-reproductive, lactating and pregnant bats may differ. However, most roosting studies

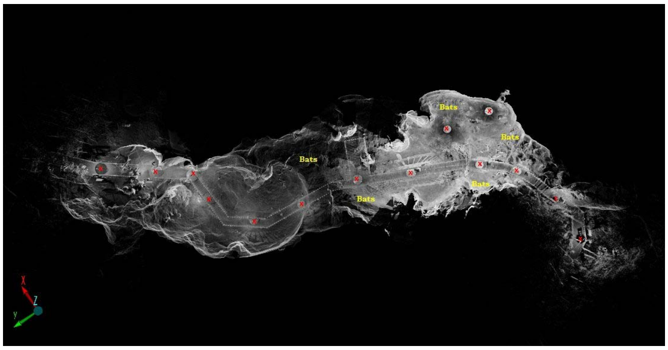

Figure 1 | The floor map of the Gua Kelawar showing the main cavern with the roosting bats. The red dots represent the scanning stations, and the areas with the roosting bats are denoted in yellow.

focus on tree-dwelling and human settlements[2,3]. We believe that the absence of a technology that allows for accurate sampling of bats in their cave roosting environments hinders research pertaining to these aspects of bat roosting behaviour. We propose a new non-intrusive method for conducting bat surveys that utilises LIDAR laser scanning technology to overcome this methodological barrier.

Results

First, the scanning process was able to capture the surface of the cave, and it produced a high-resolution, 3D model of the cave with the bat distribution and the cave topology visibly differentiated. Prior methods that were used to increase the accuracy of population counts include digital imagery[4,5], thermal imaging[6–8] and automated image recognition techniques[9]. However, these counts do not provide the spatial context and distribution information of the roosting bats. The LIDAR scan generated sufficient spatial information for the development of the 3D model of the species map. This map will serve as a digital documentation of the characteristics of an underground space and thus provides an accurate representation of the species' habitats. As the laser scanning technology requires a line of sight, we performed a preliminary survey of the cave floor to find the best location that allowed the laser scans to sweep the cave in an uninterrupted path. A total of 14 scanning stations were chosen within the cave to ensure every surface of the interior was included (Figure 1). We also examined the laser points emitted by each scanning station to ensure the point clouds created by the composite of the multiple scans sufficiently overlapped each other and minimised data shadows (Figure 2).

Second, the population count of the roosting bats was calculated automatically using a detection algorithm that measures the intensity of the returning laser (Figure 3). Third, we successfully achieved species recognition by feature extraction. One of the roosting species was identified as *Hipposideros larvatus,* and it was confirmed by live capture (Figure 4). During the survey, the accompanying team of biologists captured and identified two cave roosting species: the *Hipposideros diadema* (Diadem Roundleaf bat) and the *Hipposideros larvatus* (Large Round-leaf Horseshoe bat). We managed to produce a more accurate roosting count of 1520 individuals, as compared with the 1284 individuals counted using the 360° omni-directional photographic methods. Additional images and information on the scanning results are available at http://birg1.fbb.utm.my/bats1/index.html. The 360° omni-directional, stitched images of the interior of the Gua Kelawar cave are available for comparison at the accompanying website http://birg1.fbb.utm.my/360/Langkawi/Gua_Kelawar/tour.html

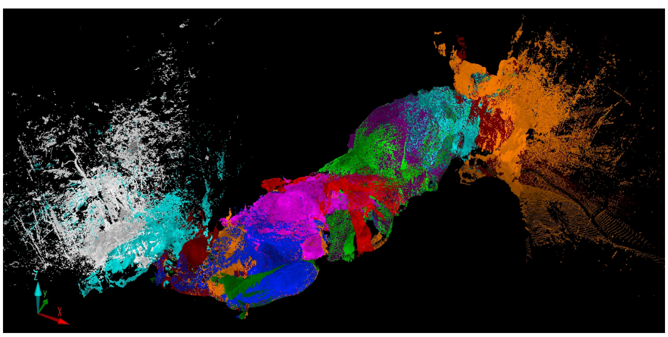

Figure 2 | The scanning points from different scanning stations are represented with different coloured points.

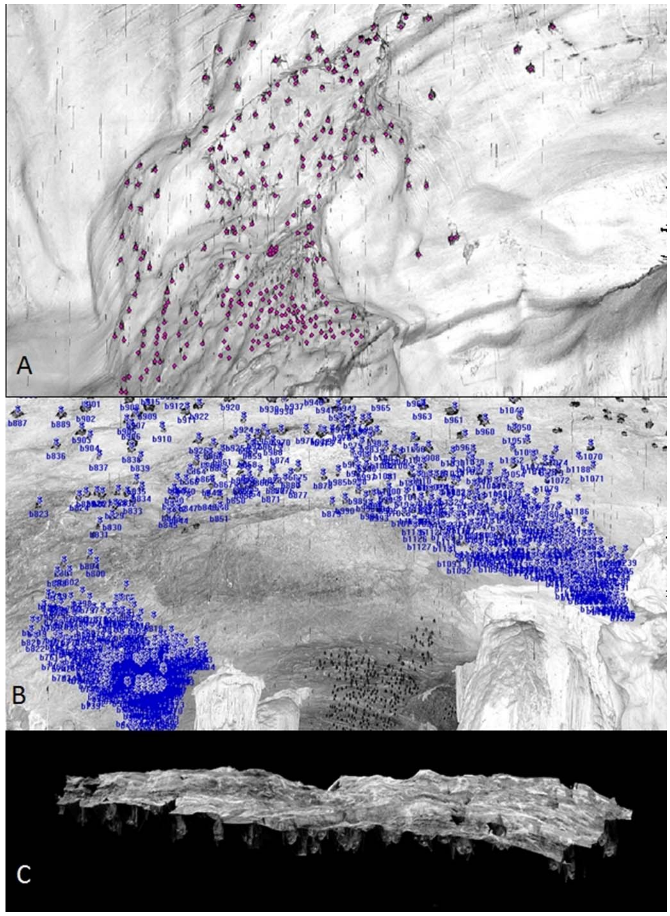

Figure 3 | The ability to differentiate the presence of bats in the scan product. A. The identification of bats' distributions in the scanned product based on difference reflectance values. B. The bats' population count. C. The parallel intersection of point cloud data.

Discussion

This study obtained several results. First, the spatial form of a cave was captured with a high-resolution, 3D model. The distribution of bats and the cave topology were visibly differentiated. The strategic positioning of the 14 scanning points along the 100 m long cave avoided any significant shadows in the point cloud. Shadows were limited to very small crevices, cave scallops and deep, narrow fissures in the cave wall. The scanner has the systematic distance error of $\pm$ 2 mm at a distance of 25 m and a field of view of 360° horizontally and 320° vertically, which are well within the scanned cave that is 22 m at its widest point. These data gaps are negligible because roosting bats hang from relatively open surfaces on the cave walls. This behaviour has enabled us to differentiate the roosting bats from the cave surface by their reduced reflectance in the laser scans. The

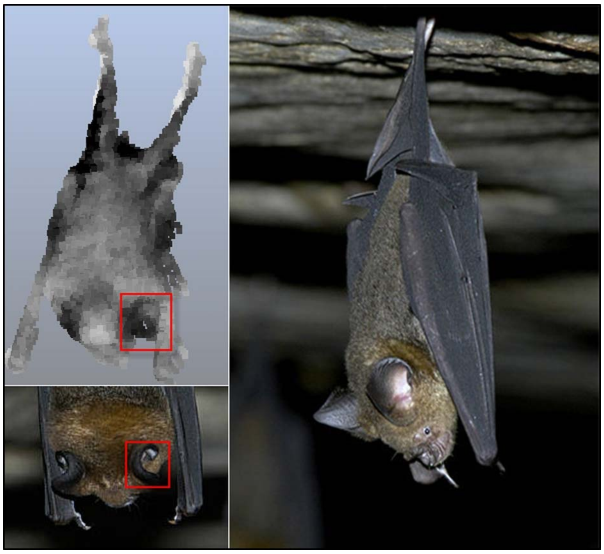

Figure 4 | Features used in the species identification of *Hipposideros larvatus* (image courtesy of Nick Baker; http://www.ecologyasia.com).

laser scanner used in the scan is the Faro Photon 120, which has an unambiguity range of 153.49 m and a speed variation of between 122,000 and 976,000 points per second. Total darkness in caves is the ideal condition for the laser pulse to travel and to calculate reflectance because the scan's quality is inversely proportional to the illumination. The previous application of airborne laser scanning had to account for various uncompensated, fluctuating atmospheric conditions, such as air pressure, temperature, and humidity, over a large distance for a continuously moving scan[10]. Negligible errors are produced by the high pulse scan rate, the relatively constant conditions within the closed confines of the cave, the static scanning stations and the relatively short distance from the scanning station to the cave surface compared to the atmospheric conditions that introduce errors in airborne laser scanning.

A method to generate 3D maps of roosting bats would provide an improvement over previous methods that utilise a 2D layout to plot the location of the bats[8]. Reports of roosting sites are often descriptive and require a significant amount of imagination on the part of the reader if they have yet to visit the described site. A 3D map would provide rigorous quantitative information that would support empirical investigation, because the hibernaculas or roosting caves can be represented in their full spatial contexts: phreatic, vadose, bell chamber, open gallery, elevated chamber or domed chamber. This method would produce better visualisation capabilities via virtual models and animations that can be repeatedly examined post-survey. An augmentation of thermal measurement tools would make it possible to characterise additional roosting parameters, such as thermal characteristics, of a roosting cave. The technology would be well suited for a thorough censusing of a large cave complex with a larger number of chambers and rooms of various sizes.

Second, the population count of the roosting bats was accurately calculated using an automatic detection algorithm. The fur of the bats significantly absorbed the laser pulse and created a large contrast between the fur and the surrounding cave surface. The distant scanning (<25 m) that was conducted using laser scanning in our method is an improvement over previous photography[4] and photogrammetry[9] methods, as they require close proximity image capture to create a mosaic composite of images. However, a significant limitation of using laser scanning on high-density clusters of roosting bats is that the returning laser pulses register the bats as one single mass of fur. A combination of other feature extraction methods on distinct, visible features, such as the bat muzzle, can then be utilised[9]. In our survey, the roosting bats did not form a dense cluster, and they are spaced over a large area.

In the 360° omni-directional photograph, only 1284 individual bats were identified. The 15% difference between the 360° omni-directional photography and the laser scanning results can be attributed to the low-light conditions; we did not use a high powered flash to minimise the disturbance to the bats. The population count of the bats conducted using the 360° omni-directional photographs utilises a manual counting method based on human recognition, and distant bats that did not contrast well in the limited light were not discernible and thus would not have been successfully identified. Although the use of photography would save time in the field, limited illumination would force observers to take images at a closer distance and a larger number of images to reduce over-counting[4].

Third, we successfully recognised species by feature extraction, and one of the scanned bats was identified as *Hipposideros larvatus,* which was confirmed by live capture. During the survey, we captured and identified two species, the *Hipposideros diadema* (Diadem Roundleaf bat) and the *Hipposideros larvatus* (Large Round-leaf Horseshoe bat), while only observing the *Rhinolophus affinis* (Intermediate Horseshoe bat) through visual identification. The LIDAR scan failed to differentiate between different species in a mixed roosting colony of more than one species; it cannot distinguish similar species, and the automated counts would reflect the aggregate number of bats but not those of a particular species. The terrestrial laser scanning was only able to detect *H. larvatus* among the roosting species because it is relatively large and the physical characteristics are sufficiently discernible within the point cloud. Therefore, we believe that differentiating specific species would require human visual interpretation, and the identification of species using laser scanning would be limited to large, distinct species.

The advantages of using LIDAR include the generation of a 3D topographical cave surface maps and the practicality of use in very low light conditions to minimise disturbance. The technology was only able to count the overall population and identify species that are easily visually identifiable and thus would not provide any advantages over existing visual identification of species. The laser scanning does generate sufficient spatial information for the development of a 3D model of species population maps and the development of digital documentation of the characteristics of an underground space. These 3D models can be archived and are amenable to repeat, post-survey visualisations and quantitative spatial analyses of roosting patterns. We believe that the development of this technique will simulate its application and open up new possibilities for roosting studies.

Methods

In this study, we used a terrestrial LIDAR, which is an optical remote sensing technology that measures the properties of scattered light to measure a distant target. It is widely used in heritage conservation, for precise measurement in automobile industries and for landform ad speleological surveys[4]. However, the application of laser scanning in biological research is a relatively new application that is limited to silviculture and forestry. Using terrestrial LIDAR, millions of high resolution points generated by the laser's pulse are merged into a composite to become a point cloud that precisely represents the inner condition of a cave and its roosting bats. The laser pulse emitted from the scanner scans the information and is reflected back to the machine that then stores the information. The outputs of the surveys are point clouds that contain the spatial coordinates x, y, z and the reflectance values. Millions of point clouds form the surface that represents the scanned object. In this case, the scanned objects were the cave surface and the bats. This created a 3D bat image that is differentiated from the cave surface and thus produced a highly detailed image of each bat without direct contact. We then spatially analysed the 3D distribution of bats' populations and generated a 3D topological structure of the cave that the bats dwell in and thus obtained a high resolution model of the cave and an accurate count of the bats and their roosting patterns.

In this study, we surveyed the Gua Kelawar cave in Langkawi (N 6° 24′ 6.6918" E 99° 51′ 32.781"), which is a member of UNESCO Global Geopark Network. The survey began in the morning to take advantage of the roosting bats. The survey team was divided into two: a laser scanning team and a photography team. A preliminary survey was performed to choose the best location to place the scanner to ensure every surface of the cave could be analysed by the scanner. We used a Faro Photon 120 laser scanner that is sufficiently portable to be deployed within the tight confines of the cave. The cave was completely scanned by the scanning team, and the data were stored for processing in a terrestrial laser scanner in the evening. The photography team immediately took a 360° image using a digital single lens reflex (DSLR) Nikon D90 with a flash that was mounted on a Nodal Ninja 3 MKII tripod as the laser scanning team moved to the next scanning station. The images were captured from a single viewpoint to maintain a constant position, but the camera was rotated to point in a different direction for each shot. A panoramic tripod head was used to keep a constant camera alignment and viewpoint while allowing for rotations and tilting between the images.

During the processing stage, we measured the reflectance of the laser pulse and determined the different reflectance values; the strength of the returning signal is influenced by the reflective abilities of the scanned surface. Therefore, the bats possess a significantly lower reflectance value due to the dark colour and physical characteristics of the bat's fur that allows it to absorb the laser pulses more compared to the higher reflectance value of the solid surface of the cave. The difference in the values between the bats' and the cave's surfaces are used to classify the point cloud and to automatically determine the number of roosting bats. A visual inspection of the point cloud is conducted to examine for any possible error in the automated process. In the 360° omni-directional photographic images, a manual count was performed for each image, and the identified bats were counted in each viewpoint. Redundant bats were omitted in each sequential station to avoid counting duplicates.

To identify a bat species, we extracted the unique and visible features of the bats, such as the head shape, muzzle, noseleaf, tragus and forearm length. These characteristics were the used to filter and classify each captured 3D shape of a bat that was identified from the point cloud. Differentiating features that were used for identification were extracted and modelled from three known cave roosting species in Malaysia: *Rhinolophus affinis* (Intermediate Horseshoe bat), *Hipposideros diadema* (Diadem Roundleaf bat) and *Hipposideros larvatus* (Large Round-leaf Horseshoe bat). A manual identification was performed using a capture and release method conducted by a team of biologist that accompanied us to the site to confirm the species present in the cave.

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Author contributions

SNA and MSS designed the methodology, conducted the experiment and wrote the paper. SAMS and NJS are the biologist who assisted in the species identifications. AA and ZM performed data analysis on the LIDAR. MNAI is responsible for the 360° omni-directional imaging and the manual counting.

Additional information

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