The Caveatron: An Integrated Cave Survey and LIDAR Scanning Instrument

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Abstract

The Caveatron is a unique handheld electronic device specifically designed as a complete survey and 3D mapping tool for caves or other underground environments. It provides a caver-friendly, self-contained system for recording all station-to-station measurements, "sketching" the passage with walk-through 3D point-cloud scanning using its integrated LIDAR, and entering data, such as station names, and reviewing line plots. Using its graphical touchscreen interface, various survey functions are quickly performed. In "Shot Mode", distance, azimuth, and inclination measurements between survey stations are recorded by simply aligning the integrated red laser to a station and activating the 4-second measurement process. 3D LIDAR scan can be quickly recorded either in "Passage Mode", by traversing (i.e. walking or crawling) toward a survey station, or in "Room Mode", where the device is manually rotating over a fixed point. The LIDAR scans 360 degrees making continuous cross-sections with a few centimeter resolution at a typical slow walking pace, allowing most scans to be completed in about 1 minute. The absolute position is continuously referenced to a special card held on a nearby survey station, avoiding inertial drift or the need for separate fiducial markers. The Caveatron is designed to be lightweight and compact with an environmentally sealed enclosure that contains a rechargeable battery, data storage, and a standard USB port for charging and data download. The LIDAR scanner is housed in a separate small enclosure that detaches so that the system can be used as a more compact survey-only tool. A spin-off design on a telescoping pole with a more advanced LIDAR was also developed to scan areas that may not be accessible to personnel. Scans from the system are easily reviewed and post-processed with custom-written PC software into 3D point clouds which can be rendered into meshed solid models for visualization or 3D printing.

Keywords: Electronic cave survey, LIDAR, mapping, 3D models

1. Introduction

Cave survey and mapping is still largely done in a traditional manner – with mechanical instruments and paper sketchbooks. While these techniques are trusted and for the most part reliable, the process is time consuming, limited in the level of detail possible, and prone to error and estimates (especially in the sketches). In recent years, cavers with electronics knowledge have begun developing devices to address some of these challenges, most notably, the DistoX (DistoX 2017), which can rapidly and accurately acquire all station-to-station shot measurements electronically, though the station names and sketch must still be recorded separately.

Other cavers have been looking at how to replace sketching with a three-dimensional electronic scan of the interior of the cave using LIDAR (Light Imaging, Detection And Ranging). Early LIDAR systems were bulky, extremely expensive and not suited to cave environments. Newer LIDAR units, while still expensive, are substantially smaller and have been successfully employed in caves, producing impressive results (Gallay et al. 2014). An even more compact system, which eliminates the tripod for in-motion scanning in caves, has also been developed (Zlot and Bosse 2014). However, these systems typically require additional support equipment, special markers to localize the system, and require technical expertise to operate. The DIY electronics hobby community has driven demand for smaller and lower cost rangefinder modules, and cavers have begun to build their own tripod-mount LIDAR systems suited for cave use (Buecher 2016). These systems must be spatially oriented and tied into the survey, requiring additional measurements or markers.

The Caveatron takes a novel approach, combining the survey instruments with a LIDAR scanner into one complete system that can replace the instruments and in some cases even the sketchbook. A major advantage of the Caveatron is that it scans while in motion, avoiding the need for tripods, special setup, or and additional equipment. The design is focused on low cost, user friendliness, and a reasonably compact and integrated package that can stand up to the cave environment.

2. Design

The design of the Caveatron initially started in 2012 as a simple tool to assist sketching plan and profile views, relying on inexpensive ultrasonic sensors for both wall and station measurements. Although this approach produced good data, the ultrasonic sensors had a wide beam and were affected by the high humidity in caves, rendering them unreliable after a couple hours of exposure. Four major design iterations gradually shifted from ultrasonic to laser based sensors, when new components were found with acceptable cost and performance. The laser sensors have much higher resolution allowing the system to be sealed against moisture and dust ingress. As the potential of the system to be a complete cave survey tool became apparent, the design and user interface evolved from an alphanumeric LCD and keypad to a more sophisticated, self-contained, sealed enclosure with a full-fledged touchscreen graphical user interface (GUI).

The Caveatron employs a modular design, consisting of a base unit and LIDAR module (Figure 1). The base unit contains the main processor, sensors, and battery. On the top is a cutout for the recessed 3.5", 480x320 pixel color touchscreen. The top also has a rail for mounting the LIDAR module and a con-

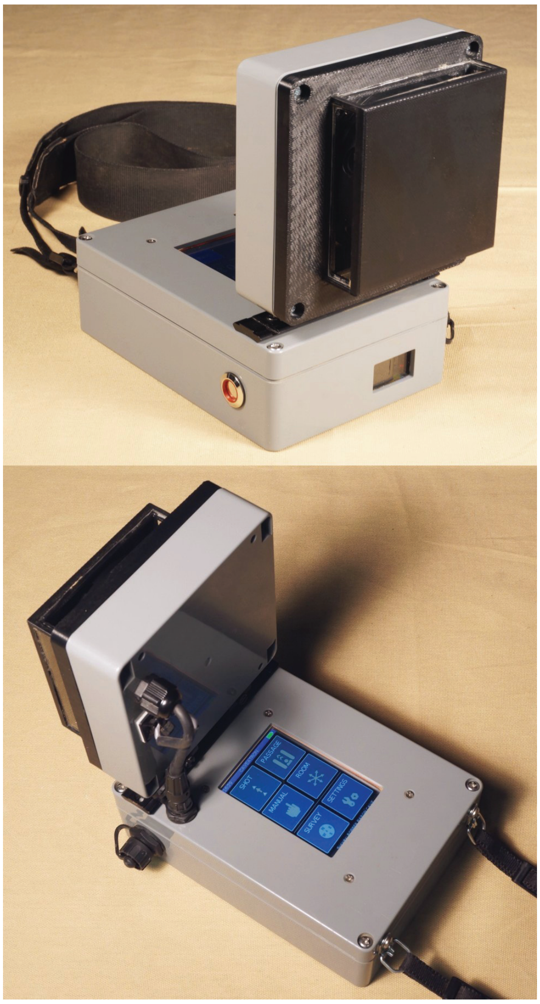

Figure 1. The Caveatron with the LIDAR module attached.

nector for the LIDAR module cable. On the right hand side is a recessed power switch, while on the left side is a capped mini-USB port used to charge the battery, download data, and update the firmware. On the front is a small window for the laser rangefinder, and on the rear are rings for the neckstrap.

The system uses an Arduino Due as the main processor. It has an 84 MHz, 32-bit Atmel ARM processor and 512 kB of flash storage, giving it the speed and capacity to handle the LIDAR data and GUI. The system is powered by a Li-ion battery pack capable of operating the Caveatron for more than seven hours. Additional electronics include power supply boards and a real-time clock/EEPROM board with separate battery backup. Azimuth and inclination measurements are obtained using an ST Microelectronics three-axis magnetometer and accelerometer with 12-bit resolution. A modified laser rangefinder provides distance readings at a 0.9 Hz sampling rate at distances up to 40 meters.

The Caveatron LIDAR module contains the LIDAR scanner, which obtains one point per degree over a 360° scan at a rate of 4.5 rotations per second. It is compact and very low cost, but has the trade-off of a limited range of four meters. The module has sealed acrylic windows for the LIDAR on all four sides and attaches to the base unit rail by thumbscrews. Separating the LIDAR from the main unit allows the system to be more compact for transport or for use without the LIDAR, if only station-to-station shot measurements are required. It also provides design flexibility to permit more advanced LIDAR modules in the future that will have greater range.

The enclosure is made from heavy-duty ABS plastic. The windows and display are recessed to reduce the risk of scratches or impact damage and each penetration has an O-ring or sealing gasket to protect against dust and moisture ingress. Although the Caveatron has not been tested for total water immersion, it does operate normally in moderately wet and muddy environments. Detailed specifications for the Caveatron are provided in Table 1.

3. Operation

A major challenge for the Caveatron design effort was to develop a simple, user-friendly method of operation based as much as possible on conventional cave survey techniques, and using normal survey stations. Measurement shots of the distance, azimuth, and inclination between stations are obtained with the Caveatron followed by a LIDAR scan of the region between stations to "sketch" the cave. One key aspect of the system is the use of a retroreflective card held on the station to which the shot is being taken. A neutral density filter is applied to the rangefinder so that valid distance measurements are obtained only when aligned with the card. Since it is nearly impossible to reliably hold the Caveatron on station while traversing (walking or crawling) without heroic effort, this approach guarantees that only correctly oriented measurements are used as absolute position references. Random hits on the card while moving provide sufficient fixed position references with interpolation providing the intermediate positions. Although the system has been designed to allow an inexperienced operator to obtain acceptable data, greater precision and denser scan coverage can be obtained through practice.

The Caveatron's custom designed GUI steps the user through three main operating modes (Figure 2). SHOT mode is used to obtain the station-to-station measurements. The operator enters the "From" and "To" station names, then places one

Table 1. Specifications of the Caveatron.

Parameter	Specification
Compass accuracy	< +/- 2°
Inclination accuracy	< +/- 1°
Distance range	> 40 m
Distance accuracy	+/- 2 mm
LiDAR range	< 4 m
LIDAR spatial resolution†	~ 3-5 cm in a 5 m wide passage
LIDAR range accuracy	< 1% of range
Approximate run time‡	7.2 hours
Enclosure dimensions (with LIDAR)	20.5 cm x 14.1 cm x 19.0 cm
Weight (with LIDAR)	1.1 kg

† *Depends on wall distance and operator speed.*

‡ *Assumes unit is continuously on and taking one shot and LIDAR scan every five minutes.*

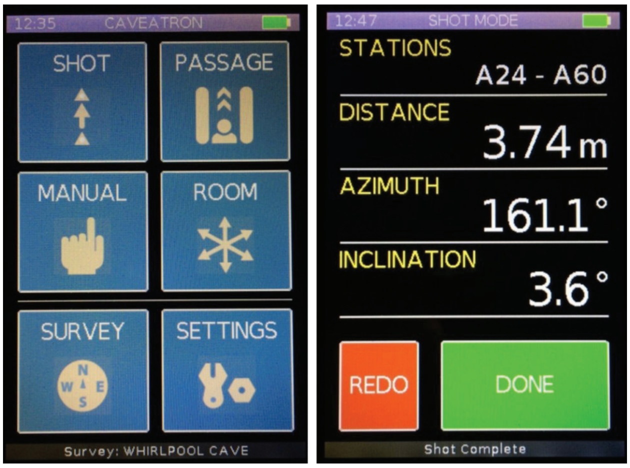

Figure 2. Sample screenshots of the Caveatron GUI including the Main Menu (left) and Shot Result screen (right).

Figure 3. The Caveatron performing a PASSAGE Mode LIDAR scan in Fort Stanton Cave. The operator (right) moves gradually toward the retroreflective card (center) held on a survey station. Photo by Pete Lindsley, courtesy BLM.

of the rear corners on the "From" station. A red alignment laser activates to align the Caveatron with the "To" station. The operator actives the shot, which takes about 3 seconds to complete, with audible tones indicating the start and finish. The measurement results are displayed and the shot can be accepted or retaken. If a problem occurred, such as the Caveatron detected significant motion or too much variability in the measured values, the shot will fail with a low-pitched tone and displayed message.

The other two operating modes are used for LIDAR scanning. In PASSAGE Mode, the operator traverses down a passage toward a station, attempting to keep the visible laser pointed toward the retroreflective card held on the station (Figure 3). The LIDAR continually spins perpendicular to the direction of motion, producing passage cross-sections every few centimeters. For each LIDAR rotation, the Caveatron measures the azimuth and inclination, with the distance measured as frequently as a valid reading can be obtained from the card. Since the position is being continually determined, there is no need for the operator to maintain a perfectly straight line of motion toward the station but can move around obstacles and take whatever path optimizes scan coverage. Periodic acoustic tones provide feedback for valid distance readings. If the operator does not hit the card frequently enough, warning tones sound and eventually the scan will abort. Errors that would yield poor data are also detected, such as excessive velocity or large angular excursions. Many traverses may be made to any given station to cover a larger area than the LIDAR can reach or to obtain additional coverage for occluded areas.

In ROOM Mode the Caveatron is held at a fixed location and is rotated in place to build up a scan of the area around it. This is useful when there is an alcove, corner, or room that may not be suited to a traverse-type measurement. The position relative to a survey station is determined by an initial reading and the unit is then rotated to the scan's starting orientation. During the scan, only azimuth and inclination readings are acquired to track the angle of each LIDAR rotation. This is the preferred mode for safely scanning pits by taking scans at periodic locations while descending.

The Caveatron GUI provides other useful functions. MANUAL Mode is used to obtain quick, readings of distance, azimuth or inclination. The SURVEY menu provides functions for initial setup, viewing survey data, statistics, and displaying a graphical line plot in plan and profile views. The SETTINGS menu provides utilities such as adjusting system parameters and displaying a live view of the LIDAR data to assist in determining the amount of coverage.

Proper calibration of electronic accelerometers and magnetometers is important to obtain accurate readings. Although the design of the Caveatron is not oriented toward very high precision, accuracy at least comparable to that obtained by an average cave survey team is a goal. Calibration can be a complex process, but effort has been made to make it as simple as possible. Most of the calibration is done only at the time of assembly. This is the case for the 12 accelerometer coefficients which are computed by carefully leveling the Caveatron and taking readings in all six orientations. The magnetometer misalignment vector and rotation offset are also determined during assembly using an outdoor calibration range. However, the other 15 magnetometer calibration values, representing the hard and soft iron corrections, have been found to drift over time (typically a few weeks), requiring user recalibration. An automatic point collection and least-squares fit routine was written to perform this computation onboard the Caveatron, only requiring the operator to continuously rotate the unit in all directions of an imaginary sphere for about 1 minute. Example residual error data after calibration is shown in Figure 4.

It was found that the presence of the LIDAR module motor impacts the magnetometer calibration. As such, two separate magnetometer calibration sets are stored with the correct one loaded at startup depending on whether the LIDAR is attached. No significant additional effect on the magnetometer was observed when the LIDAR motor was actively spinning. To easily facilitate updates, all calibration and hardware parameters are stored on an independent EEPROM chip separate from the firmware.

4. Post-Processing

Data is stored on a built-in SD card in two plain-text files for each survey trip. The survey file contains the station shot

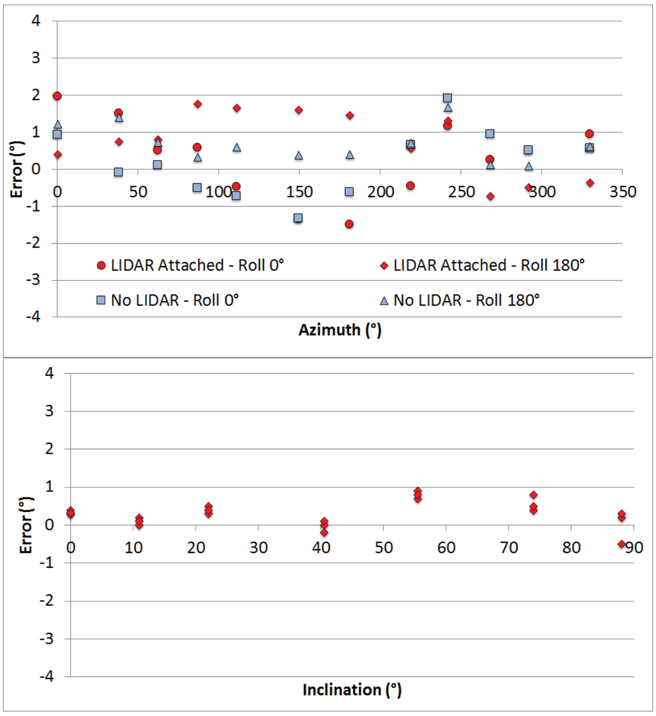

Figure 4. Residual measurement error of one unit after calibration. The azimuth error (top) is shown for different configurations and orientations. The inclination error (bottom) shows three sets of measurements taken at different times.

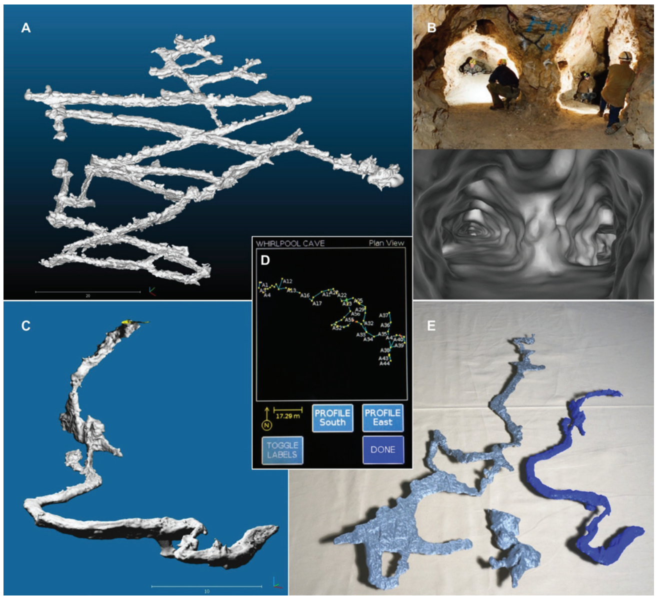

Figure 5. Example data from the Caveatron: A – Rendering of about 550 m of Robber Baron Cave in San Antonio, TX; B – Interior of Robber Baron Cave showing a comparison of a photo and the rendered data; C – Rendering of the entire 98 m-long Cricket Cave near Boerne, TX; D – Screenshot of the line plot displayed on the Caveatron from a survey of 229 m of Whirlpool Cave in Austin, TX; E – 3D printed cave models of Whirlpool Cave, Canyon Wren Cave, and Cricket Cave (left to right).

data and is formatted for Walls – a freely available cave survey processing program (Walls 2017). A separate LIDAR file contains only minimally processed scan data, since the Caveatron processor is limited in its capabilities. Noise filtering, data smoothing, and conversion into an x, y, z point cloud is performed in post-processing using a program for Windows or Mac platforms called "Caveatron Process".

The first step is to generate a station coordinate file to link together the LIDAR scans. This is created from the stored survey file either in Walls or directly in the Caveatron Process application. Using Walls has the advantage of utilizing its powerful tools to optimize the line plot when loop closures are present as well as geo-referencing the survey. In the Caveatron Process software, the line plot can be viewed, global references set, and a magnetic declination applied.

The second step is to load the LIDAR file to review and process each scan. The software automatically removes bad data and noise, interpolates the Caveatron location between fixed position measurements, and filters excessive motion. The GUI allows the user to step through each rotation of the scan, showing cross-section, plan and profile views. The occasional bad data that slips through the filters can also be selected for removal. A normal vector is computed for each point based on the vector toward the LIDAR and the position of neighboring points. This vector is important if the point cloud is to be meshed and defines the direction straight in from the cave wall. The point cloud is stored as a delimited text file, which can be viewed in a program such as CloudCompare (CloudCompare 2017). Another program, Meshlab (Meshlab 2017) has the capability to render a meshed model of the cave, allowing it to be explored virtually – both inside and out. An accurate-scale 3D-printed physical model of the cave can also be generated.

5. Testing

Four complete systems have been built and the Caveatron has been evaluated in several caves in south Texas, for which some sample data is shown in Figure 5. It was found that in a typical mix of walking and hands-and-knees crawling passage, with effort taken to ensure good scan coverage, the survey rate is generally about 40 meters per hour. A variety of caves have been scanned including those with solutional and breakdown mazes, small and tight crawls, large rooms, wet and muddy areas with dripping water, pits, and shelter caves. For some of these trips, the Caveatron was used for a full day of survey and did not exhaust its battery. The Caveatron performed well in all of these tests without significant problems. Rendered and 3D printed models have revealed previously unseen morphology such as bedding planes, passage meanders, and other relationships that were not obvious on the traditional maps.

A major test of the Caveatron was at the Fort Stanton Cave Study Project in New Mexico in October 2016. Part of this project includes an ambitious goal of producing a 3D model of as much of the 50 km long cave as possible. During this trip, both the Caveatron and a different LIDAR system that is stationary but has a longer range (Buecher, 2016) were employed. It was found that the two systems were complimentary, with the Caveatron being best suited for small to medium sized passageways and the other system most effective in larger rooms. Data from the two systems combined well in overlap areas, giving confidence in the accuracy of both designs.

6. Telescoping-Pole Cave Mapper System

A spin-off design of the Caveatron has been developed for the City of Austin, Texas that allows for mapping the near-entrance interior of caves without requiring human access. The system is intended for use when there is concern about

Figure 6. Telescoping pole cave mapper system.

sending personnel into caves that have been newly uncovered through construction operations, where the entrance area may be unstable. This design places the scan head on the end of a 7.5-meter telescoping pole, which is inserted into the cave (Figure 6). The head contains a professional-grade LIDAR with a 30-meter range and a 25 Hz scan rate. Unlike the Caveatron, this LIDAR is oriented along the axis of the pole and rotation of the pole is used to build up the 3D scan. The head contains an inertial measurement unit to determine the head's orientation, illumination LEDs, and a high-definition video camera to remotely visualize the cave and guide the head into position. Since portability was less of a constraint with this design and the LIDAR data rates are high, a Windows laptop PC is used to control the system and record data. Custom software was written to allow the operator to preview the scan, record data, and post-process the results into a point cloud.

In operation, the head is inserted into the cave and the pole extended to guide it to the scan location. To assist in moving the head around obstacles, a spring-tensioned pull-cord provides one axis of articulation. Once in place, the operator uses a separate laser rangefinder to measure the distance from a reference point at the cave entrance to a spot on the rear of the scan head. The distance value is entered into the software to start the scan and then the operator slowly rotates the pole at least 180° to complete the scan. Additional scans to obtain greater coverage can be conducted from the same reference point by moving the head to a new location and repeating the process.

7. Planned Developments

We continue to evaluate potential new components for the Caveatron to enhance its capabilities. A new, relatively low cost LIDAR scanner became available at the beginning of 2017, which can address the scan range limitation of the current LIDAR. The new scanner should increase the range to more than 25 meters with only a slight reduction in scan rate versus our current module. Its similar interface and form factor will allow it to be interchangeable with the existing LIDAR. Another planned improvement is to fabricate a custom printed circuit board to eliminate much of the wiring and provide an integrated baseplate with plug-ins for the each sub-assembly. Software revisions continue to be developed to add features, improve processing, and eliminate bugs. We hope to eventually provide the Caveatron for sale on a limited basis and to open-source the code and documentation online so that anyone can build their own.

Acknowledgements

The authors would like to acknowledge Gregg Williams for machining the enclosure and 3D printing cave models, Matt Capps for the design of the LIDAR head cover, Alan Craig for mechanical design of the pole-based system, Jill Orr for the GUI icons, and Ellie Watson for the Caveatron logo. We would also like to thank the many people have helped test the system and provide ideas for improvements.

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