Augmenting geological field mapping with real-time, 3-D digital outcrop scanning and modeling

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ABSTRACT

Hand scanners are compact, lightweight, and capable of generating 3-D digital models. Although they do not compare to conventional methods (terrestrial laser scanning and photogrammetry) in terms of coverage, resolution, and accuracy, they offer increased mobility, speed, and real-time processing capabilities in the field. This study investigates the use of hand scanners for real-time, 3-D digital outcrop modeling to augment geological field mapping campaigns and highlights the advantages and the limitations. The utility of incorporating hand scanners as an additional tool for augmenting geological mapping is assessed based on 41 outcrop scans from the Gould Lake area, which is located 20 km north of Kingston, Ontario, Canada. The 3-D digital outcrop models gathered included two distinct metamorphic lithologies (marble and quartzofeldspathic gneiss) measuring up to 2.5 m high × 7 m long with an average surface area of 18 m². This average scan size would take less than 10 min to capture, result in ~18 million individual points per scan, and provide a spatial resolution of ~1 cm for outcrop features. Throughout the course of the investigation, the main benefit of capturing multiple 3-D digital outcrop models was the ability to integrate this real-time, in situ geospatial, and geologic information across multiple visualization scales. This utility and retention of outcrop-scale geospatial information was shown to enhance the understanding of multi-scale geological relationships.

INTRODUCTION

Three-dimensional digital outcrop models are colored point clouds scattered in 3-D space from which a surface model can be generated, visualized, and interacted with by translating or rotating the digital model (Xu et al., 2000; Trinks et al., 2005). To name a few, applications for 3-D digital outcrop models include stratigraphic modeling (Bellian et al., 2008; Enge et al., 2007), structural analysis (Triantafyllou et al., 2019), geohazard monitoring (Abellan et al., 2016), reservoir characterization (Hodgetts, 2013; Qiao et al., 2015), and assessing engineering geology outcrop parameters (Sturzenegger and Stead, 2009).

The technological advancement of hand scanners has been driven by various multidisciplinary applications in fields such as forensics (Komar et al., 2012), architecture, archaeology, art, and historical documentation (Munkelt et al., 2007; Márquez-González et al., 2017), construction (Sepasgoazar et al., 2017; Omar and Nehdi, 2016), as well as medicine and health sciences (Cau et al., 2016; Shinkai et al., 2017). The main advantages of hand scanners in these fields are their mobility, ease of use, and rapid generation of models in real-time. Despite the increasing use of 3-D digital outcrop models in the geosciences and the technological advancements in hand-scanning technology driven by various multidisciplinary applications, the use of hand scanners in the field to map outcrops is not routine. Three-dimensional digital outcrop models are typically acquired for post-processing and analysis using high-resolution terrestrial laser scanners (TLS) and/or photogrammetric methods (Telling et al., 2017; Tavani et al., 2014). Given the technological advancements in hand scanners and their portability, this paper highlights how hand scanners can be used for real-time, 3-D digital outcrop modeling to augment traditional and digital geologic field mapping via spatially located outcrop annotations, interactive analysis of spatial data at the outcrop scale, and increased data retention from the field. In particular, the study investigated (1) what additional information hand scanners can provide for a field geologist, (2) how hand scanners can be incorporated into a geological field mapping workflow or exploration campaign, (3) what geological applications can use the acquired data, and (4) how practical the use of hand scanners in the field is with a particular focus on geological outcrops.

DATA ACQUISITION METHODOLOGY

Handheld 3-D Scanners

Two handheld 3-D scanners, the DotProduct DPI-10 and DPI-10SR, were used in the geological mapping campaign to assess and compare overall utility, performance, and data quality parameters. The specifications of these two scanners, the PrimeSense Carmine 1.08 and Carmine 1.09 sensors, respectively, are outlined in Table 1. It is worth noting that many other camera systems can be integrated with a DotProduct scanner, but the two selected are well suited for the outcrop scanning applications. The main difference between the two scanners is that the DPI-10SR (the PrimeSense Carmine 1.09 model) is a short-range variant that provides a higher point density and resolution (spatial resolution of 0.1 cm and depth resolution of 0.5 cm) at the closest scan range of 0.3 m. In contrast, the longer-range, DPI-10 version (the PrimeSense Carmine 1.08 model)
provides a lower density and resolution of scanned points (spatial resolution of 0.2 cm and depth resolution of 1.0 cm) at the closest range of 0.6 m. The general tradeoffs between these two scanners are that the DPI-10 can scan at an increased distance from the outcrop, up to 3.5 m, which provides a relatively wider field of view and shorter scan time at the cost of a lower data resolution. The DPI-10SR can scan at a closer distance to the outcrop, which provides higher resolution data while sacrificing coverage efficiency and increasing scan time.

Both hand scanners generate a colored, 3-D point cloud of the geologic target under investigation. The spatial component of the model is generated by actively emitting points of infrared light onto the target surface that are reflected and captured by an infrared detector. The infrared detector converts the captured points of infrared light into 3-D spatial components ($X$, $Y$, $Z$). A red, green, blue (RGB) camera attached to the scanner passively returns four corresponding light parameters at each of the captured spatial coordinates. These four parameters include intensity ($I$), red ($R$), green ($G$), and blue ($B$) light values. The intensity, red, green, and blue light levels are encoded as a number in the range of 0–255, with 0 meaning zero light and 255 meaning maximum light amplitude. Each data point captured by the scanner, as shown in Figure 1, results in seven parameters including three spatial components and four light intensity and color components ($X$, $Y$, $Z$, $I$, $R$, $G$, and $B$). When operating the scanners, the spatial coordinates ($X$, $Y$, $Z$) of the data points are initialized at the beginning of the scan (0, 0, 0) based on the starting position and orientation of the scanner. The scan scene is then continually updated and calculated based on the relative position and orientation changes of the hand scanner throughout the survey. Finishing the scan at the starting position to close the loop (closed traverse) is recommended, which provides a means to assess error of closure that is further used in the adjustment of the traverse (Davis et al., 1966).

### Three-Dimensional Digital Outcrop Model Acquisition

Unlike stationary scanning techniques (terrestrial laser scanners), where the scanner field of view rotates in place to capture an entire scene, the hand

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**TABLE 1. MANUFACTURER SPECIFICATION FOR THE HAND SCANNERS USED IN THIS CASE STUDY**

| Parameter                      | DotProduct DPI-10SR | DotProduct DPI-10 |
|-------------------------------|----------------------|-------------------|
| Continuous scanning battery life (hrs) | 2–3                  | 2–3              |
| Scanner mass (kg)             | 1.4                  | 1.11             |
| Scanning range (m)            | 0.3–2                | 0.6–3.5          |
| Spatial resolution (cm)       | 0.1                  | 0.2              |
| Depth resolution (cm)         | 0.5                  | 1                |
| Operating temperature (°C)    | 5–33                 | 5–33             |

*Note: For reference, see DotProduct LLC, [https://www.dotproduct3d.com/dpi10.html](https://www.dotproduct3d.com/dpi10.html) (accessed October 2020).*

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![Figure 1. The DotProduct DPI-10SR hand scanner with an annotation on each sensor (left) is shown with a schematic of the scanned point cloud output with seven parameters (right).](http://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/doi/10.1130/GES02452.1/5518599/ges02452.pdf)
scanners have one continuous field of view that does not rotate. To capture a scene with a hand scanner, the field of view must be varied through physical movement of the scanner by the operator. Walter et al. (2020) show a video example of field geologists physically moving the hand scanner to capture an outcrop. The relative decrease in overall scan resolution and quality is traded for an increase in mobility and versatility in the field as the operator can move the hand scanner wherever he or she can physically reach. This ability has the potential to limit blind spots that are hidden from a stationary scanner’s field of view within single scenes and can help in the capture of crevasse orientation and rounded outcrop flanks. This also allows for 3-D outcrop faces to be gathered within individual scans without the need to mesh multiple stationary scans as an additional processing step. The coordinate system assigned to the 3-D digital outcrop model can be assigned manually using the plane detection feature of the scanner or automatically based on the initialization of the scan (orientation of the hand scanner upon starting the scan). Generally, the best scanning practice is to start at one long axis of an outcrop and progress in a consistent direction to fill in the scan area until the outcrop length of interest has been captured. An example of this scan progression is presented in Figure 2, where the outcrop scan was initialized at the right side of the outcrop, as shown in blue, and progressed down the horizontal axis of the outcrop (X-axis) toward the left, where the outcrop scan was completed (red).

The location of the hand scanner when the capture was initialized is marked by the origin point (red star). This first capture scan is highlighted by a dark blue rectangle that marks the initial rectangular field of view of the scanner at the start of the survey prior to any translations or rotations of the scanner. Areas where the color scale overlaps, for example light blue on dark blue (X = 0 m) and red on yellow (X = 6 m), are areas where the operator changed the orientation of the scanner relative to the outcrop at a later instance within the scan to capture points from a different orientation. The scan was conducted toward the left; however, as the scanner looks back toward the right it fills in areas of the scan from this new vantage point that were not previously captured (shadows). Continually translating the scanner down the long axis of the outcrop face (X-axis) moving in one direction while rotating the scanner in place (both X- and Z-axes) to look in both the down outcrop and up outcrop directions.

Figure 2. A true color 3-D digital outcrop model (bottom) of the quartzofeldspathic gneiss outcrop #3 was captured from the Gould Lake area with the corresponding scan progression plot (top) demonstrating the movement of the scanner from right (blue) to left (red) along the outcrop.
allows for fewer shadows in the scan. The majority of new data points are added into the scan with each horizontal translation down the outcrop by the operator, with rotations about the two axes filling in the areas of shadow observed from the previous perspective. Varying the scanners’ distance from the outcrop (Y-axis) was also beneficial to allow a better depth estimation of the outcrop face, particularly on smoother and flatter surfaces. However, to obtain the highest point density and resolution, the scanner should operate as close to the outcrop face as possible. Due to the varying orientations of the scanner and distances from the outcrop, the resolution of the scan will vary throughout the digital outcrop model. Overall, the quality of the scan is dependent on the operator’s ability to manipulate the scanner’s field of view relative to the outcrop face in a way that captures the outcrop from as many angles, orientations, and distances as possible. This will ensure that the seven parameters (\(X, Y, Z\); rotations around \(X, Y, Z\); and scale) needed to create a 3-D point cloud are varied to obtain a more robust solution. A video presentation that gives an overview and discussion of this optimal point capture technique using the hand scanner is included in Walter et al. (2020).

To aid in this process, the DotProduct scanning software’s user interface is designed to facilitate the scanning procedure by providing information on the achieved point capture density throughout different sections of the scan in real-time, as is illustrated in Figure 3. The interactive feedback display allows the operator to visualize which sections of the hand scanner’s field of view have been captured and incorporated into the digital outcrop model and also indicates the relative point density and resolution that has been achieved in different areas of the scan. The real-time video feed of the scan scene displayed on the hand scanner’s graphical user interface will be shaded (gray) to indicate that the scanner has captured data points within the targeted area. As the resolution of these captured scenes increases via movement of the scanner, the gray shading will change through light yellow, yellow, light green, and finally dark green. This real-time feedback provided to the operator who is conducting the scan allows him or her to target specific points at specific resolutions and ensures that the necessary geological features of interest within the outcrop have been scanned. The operator also has the option to take multiple high-resolution images throughout the scan with the field tablet’s RGB camera. A high-resolution photo can be taken at any point throughout the scan as shown in Figure 3. These high-resolution photos are automatically draped as RGB textures onto the 3-D geometric model of the digital outcrop. The orientation and position of the high-resolution photo’s focal point are also automatically incorporated within the modeling space when the image is captured based on the location. Taking several high-resolution photos that...
are draped as RGB textures onto the outcrop scan allows geologists to identify and compare features of interest within the relatively lower-resolution, colored point cloud data. The high-resolution images can also be viewed separately outside of the modeling space as demonstrated in Figure 4.

In-Field Hand Scanner Performance

Despite using two different operators equipped with either the short-range (DPI-10SR) or long-range (DPI-10) hand scanners, the scanned outcrop data collected was similar and consistent when using the outlined methodology. A total of 41 outcrops, \( n \), were scanned using the hand scanners, and several of the field performance parameters of the scan were documented with descriptive statistics that are summarized in Table 2. The biggest factor that influenced the scanning time and resulting number of points is how densely the operator sampled an outcrop; scanning a single area for a longer time results in a denser point cloud. Other factors influencing the amount and quality of data recorded include the amount of vegetation or sunlight present, operator height, outcrop morphology, and accessibility.

The close-range hand scanner performed more consistently over a wider variation of targets as it was able to scan outcrops with varying degrees of vegetation coverage and higher light intensities than the long-range scanner. When scanning in denser vegetation and brush (ferns, long blades of grass, leaves, moss, deadfall, and small tree branches), the long-range scanner omitted areas of the outcrop around these irregular and thin 3-D features. This is attributed to the lower resolution of this scanner, which resulted in areas around these small discontinuous features being omitted. For both hand scanners, the total scannable area of an outcrop is limited by the areas of the outcrop the operator can physically reach when scanning tall vertical outcrops and by the ground accessibility/safety, which restricts how close an operator can get to the outcrop. The hand scanners faced other limitations when scanning geological outcrops, and based on the study involving the 41 outcrop scans, the following recommendations, mitigation strategies, and suggestions are presented.
### Vegetation

When permittable, remove as much loose vegetation and brush as possible to allow the scanner to have a clear, unobstructed line of sight to the outcrop surface. This ensures that the highest possible quality of the target feature (outcrop) is captured without sections being omitted or blocked from the field of view. Vegetation that causes more serious omissions within the point cloud data are small saplings, draped elongate vegetation-like ferns, and thin tree branches that are offset in front of the outcrop face. These types of vegetation can prevent the scanner from focusing on the outcrop surface or leave a significant area of shadow on an otherwise clear outcrop face. Vegetation such as moss and lichen are of less concern as these are more regular and form to the surface of the outcrop, which provides a more uniform surface for the scanner to capture. Additionally, removing vegetation prior to scanning can reveal any important outcrop surfaces where measurements or observations have been taken. This type of vegetation mitigation procedure is more in line with a traditional field mapping campaign conducted without a hand scanner, as geologists typically must remove obstructing vegetation on some outcrops to aid in the identification and measurement of specific features.

### Lighting

It is important to consider the level of direct, natural lighting that is present on the outcrop for this type of infrared hand scanner: dawn, dusk, and overcast skies where the outcrop is not illuminated by direct sunlight are optimal for scanning using this model of hand scanner. This is because the reflection of direct sunlight off the surface of the outcrop overpowers and saturates the infrared receivers of the scanner, which leads to the omission of data at these locations. This issue arises as these scanners and their infrared sensors were designed for indoor use and not for scenes with high natural light intensities, such as direct sunlight in the outdoors. As our goal was to demonstrate the utility of real-time digital hand scanners despite this limitation, we had to take care to plan traverses with the scanners in ideal lighting conditions (dawn, dusk, and overcast skies). Presently, this limitation has been mitigated by the introduction of camera, infrared, and light detection and ranging (LiDAR) sensors, which were designed specifically to tolerate outdoor light conditions (e.g., Intel RealSense depth cameras D415 and L515). However, it is still advisable to have consistent lighting conditions throughout the scanning area to limit any potential variability.

### Coordinate System

The coordinate system for the 3-D digital outcrop model is initialized in real-time at the beginning of each scan, and the location of the scanner is given the coordinates \((X = 0, Y = 0, Z = 0)\) within a local coordinate system. The positive and negative directions of these axes are set based on the orientation of the scanner when the scan is initialized. Every data point captured within the scan is referenced based on the relative distance to the origin along the set axis. Therefore, it is recommended that the scan be initiated with the positive Z-axis of the scanner oriented in a vertical direction (the camera pointed sub-horizontal). This initialization procedure aligns the vertical, Z-axis of the scanner with the gravity vector or plumbline. Secondly, prior to initiation of the scan, it is recommended that the scanner’s X-axis be aligned to true geographic North by means of a field compass. This procedure allows the operator to set the local coordinate system of the scanner to X = North–South, Y = East–West, and Z = up–down. This subsequently allows for the conversion of the scanner’s local coordinate system into a global coordinate system by correcting for the origin of the scan. As this scanner was developed for indoor applications, the plane detection feature of the scanner’s software would automatically assign X, Y, and Z coordinates to the right angles formed by the walls and the floor of rooms being scanned. However, when applying this hand scanner to geologic applications in the outdoors, these geometries typically do not exist, and the method described was found to be the most efficient. A future software update may allow the internal inertial measurement unit (IMU) to automatically assign a coordinate system (North, East, and Up) when in the outdoors.

A field tablet’s built-in global positioning system (GPS) receiver could provide an adequate estimate of the scanner’s true geographical location (within 3–5 m). For applications that require a more accurate scanner origin measurement (< 1 m), differential GPS could be used.

### Operational

The scanning angle and distance to the outcrop should be varied continuously by the operator to maximize the coverage, perspectives, and captured

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**Table 2. Descriptive Statistics of Field Performance Parameters for the Short-Range and Long-Range Hand Scanners**

| Variable                      | Short-range scans (n=19 outcrop scans, target distance: 0.3–2 m) | Long-range scans (n=20 outcrop scans, 0.6–3.5 m) |
|-------------------------------|---------------------------------------------------------------|--------------------------------------------------|
| Time to scan (min)           | Mean 9.1, σ 5, Min 3, Max 23                                 | Time to scan (min) 7.6, σ 4.1, Min 1, Max 15     |
| Outcrop length (m)           | Mean 7.5, σ 6.3, Min 1.8, Max 29                            | Outcrop length (m) 6.8, σ 3.4, Min 2, Max 13.2   |
| Outcrop height (m)           | Mean 2.7, σ 0.8, Min 1.4, Max 4.2                           | Outcrop height (m) 2.4, σ 0.8, Min 0.5, Max 3.3  |
| Outcrop area (m²)            | Mean 20, σ 14.7, Min 2.7, Max 58                            | Outcrop area (m²) 18.3, σ 1.6, Min 1, Max 38.3   |
| Number of points (million pts) | Mean 18.3, σ 10, Min 2, Max 41.8                          | Number of points (million pts) 16.9, σ 11, Min 3.3, Max 36.6 |

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**Variables in the table include:**

- **Time to scan (min):** The duration required to complete the scan.
- **Outcrop length (m):** The length of the outcrop measured in meters.
- **Outcrop height (m):** The height of the outcrop measured in meters.
- **Outcrop area (m²):** The area covered by the outcrop in square meters.
- **Number of points (million pts):** The total number of points captured during the scan, measured in millions.
point density. The procedure that is recommended would be to start the scan at the upper end of the scanner’s range (top 20% of its range), which would be ~1.5–2 m for the short-range scanner, and then to move the scanner closer to the outcrop, which would fill in this initial scan area at a higher resolution. The operator should then back away again to the upper end of the scanner’s range and translate horizontally into the next relatively wide angle (far away) frame. Once this wide-angle shot is captured, the operator should again move the scanner closer to the outcrop within the lowest 20%—0.3–0.5 m—and fill in this second scan area at a higher resolution. The exception this time is that the scanner should be rotated up and down as well as side to side to overlap with the previous scanned area from this new perspective. This ensures that any shadows missed in the first scan perspective, such as an oblique view of a crevasse, are captured from this new, adjacent scan orientation. This procedure can be undertaken by an experienced operator aided by the active user interface, which highlights areas captured in high-resolution versus areas that were not adequately sampled.

Redundancy

For more efficient scans, start at one end of the outcrop’s long axis and work continually in one direction to ensure that all shadow areas are captured. This procedure is most effective when the previous translation procedure is applied with three main scan geometries: (1) a forward-looking oblique scan (in the direction of main translation along the outcrop) of the next upcoming section of outcrop to be scanned, (2) a down-looking scene perpendicular to the dominant plane of the outcrop directly in front of the scanner, and (3) a back-looking scene of the previous area of outcrop that was scanned. This procedure is more important for outcrops that have significant 3-D, blocky textures where shadow areas exist between adjacent perspectives. This procedure results in redundant scenes from different orientations as viewed through the user interface; however, only the areas of shadow will be recorded as new data points within the full outcrop scan. This ensures that memory is not filled with unnecessary data.

Augmentation

High-resolution photos should be taken by the hand scanner from the central position perpendicular to the outcrop face. Depending on the level of detail required for the specific outcrop, these photos can be taken from the wide-angle position further away from the outcrop, 1.5–2 m, or they can be taken in a denser array of more tightly spaced, higher resolution photos closer to the outcrop, 0.3–0.5 m away. The downside to the latter is that there will typically be four to nine more photos required at the closer distance to cover the same area. The photos can be taken with an approximate 15% overlap between subsequent frames. This procedure is commonly used in photogrammetry to ensure complete coverage. Presently, there is not any built-in feedback within the user interface to determine what areas of the outcrop have been covered by photos. The areas of the outcrop that have been covered have to be estimated by the operator.

Scale

A reference object can be scanned into the outcrop scene to serve as a common scale. For consistency, it is recommended that a flat, regularly shaped object such as a field notebook or scale card of sufficient size (10 cm × 10 cm) be used as opposed to an irregular, blocky or elongate object, such as a geologic hammer.

Real-Time Processing and Use in the Field

Upon completing a scan, the 3-D outcrop model becomes immediately available to the geologist for viewing within the field. This allows for real-time inspection of the high-resolution images, annotation of geometric measurements of the outcrop features, and the creation of custom feature-specific annotations, all while still providing direct access to the outcrop. Geometric measurements the hand scanners can currently compute from the 3-D point cloud data gathered are distance calculations such as length, width, and height between data points, the approximate calculation of surface areas and simple volumes, as well as the detection of planar features. Presently, to incorporate geology-specific measurements such as strike and dip, measurements are taken with a compass and then annotated and located within the 3-D digital outcrop model. Hand scanners for structural mapping in underground environments have developed algorithms to automatically calculate strike and dip measurements based on the 3-D point cloud model (Gallant and Marshall, 2016; RockMass Technologies Inc., 2021). This automated functionally is expected to be further developed for real-time hand scanners applied specifically to geologic applications.

The operator can also scroll through the different sections of the outcrop model and see where along the outcrop the draped high-resolution images were taken, including their orientations as shown in Figure 4. The capture of the 3-D digital outcrop model and high-resolution images in addition to the annotation of geometric measurements within the modeling space can be used together to increase the amount of information retained from the field. An example of adding custom annotations to highlight two different lithologies is shown in Figure 5, where two boulders are tagged and labeled. All of the information gathered within the digital outcrop models (spatial information by the hand scanner and annotated information by the field geologist) can be exported in a variety of different formats that include DP, PTS, PTX, PLY, PTG, E57, LAS, and LAZ.

Geological Applications of Acquired 3-D Point Cloud Data

The acquired 3-D point cloud data captured by the infrared and RGB camera sensors can be utilized to characterize specific geological targets and
applications. The infrared sensor records the spatial extent of the outcrop or geological object of interest, which allows for the estimation of geometric measurements. This can include measurements such as the length and height of an outcrop and the distance between joint spacing and volumetric/surface area calculations for irregular objects. The RGB camera sensor captures the color and light intensity reflected off objects within the scanned scene and can be used to characterize/segment/classify different lithologies based on the recorded intensity of the reflected light values.

The red, green, blue, and intensity values captured by the RGB camera sensor were used to semi-autonomously classify distinct lithologies such as the shale and sandstone units from the Grimsby Formation in the Paleozoic sequence of the Niagara Escarpment as shown in Figure 6. By using the red, green, blue, and contrasting intensity values of the darker shale and lighter sandstone, a user-defined threshold and automatic filtering algorithm was applied to predict the lithology of each scanned point, which achieved an accuracy of 95% when compared to a manually labeled ground truth point cloud. The hand scanner’s increased mobility also allows for the semi-automatic lithological characterization workflow to be applied at locations that cannot be accessed with a terrestrial laser scanner. For example, Sturzenegger and Stead (2009) and Walton et al. (2016) discuss how occlusions and orientation bias often result from the fixed position of TLS systems. This can be mitigated with the hand scanners since the operator can move around the outcrop to ensure complete capture via multiple orientations.

The scanning and creation of a 3-D point cloud model for aggregate piles, boulders, or other geologic features allows for volume calculations and weight estimations. These estimates may be obtained in real-time and in situ. Conversely, the 3-D point cloud models can be used to estimate the amount or weight of material that would be required to fill a void space. Other complex geometric measurements that could be made include estimating volumes of mass wasting failures (Derron et al., 2005; Kerle, 2002) and mapping rock discontinuities (Cacciari and Futai, 2016; Haneberg, 2008). Two volume estimates of aggregate piles at a construction site within the greater Toronto area were made using the infrared sensor’s spatial output as shown in Figure 7. While this is a proof of concept to demonstrate a potential use for the 3-D point

Figure 5. Custom annotations for a 3-D digital model show the labeling of two different boulders.
Figure 6. Lithological classification of a dark red shale and sandstone with an achieved accuracy of 95% using the red, green, blue, and intensity values as inputs to traditional machine learning workflows. The incorrectly classified points correlate with shadowed areas that change the intensity and color of light reflected off the outcrop.

Figure 7. Volume estimates shown are based on the scan geometry of two aggregate point cloud models.
cloud data, a full-scale study would need to be conducted to evaluate if the accuracy level achieved was acceptable compared to that of other methods and standards, such as photogrammetry.

**GOULD LAKE GEOLOGIC MAPPING CASE STUDY**

The Gould Lake area is located 20 km north of Kingston, Ontario, within the Frontenac Axis of the Canadian Shield. The geology in this area is a mix of metamorphic and intrusive rocks of Precambrian age and comprises a rugged, rolling topography with lakes, streams, and marshes filling topographic depressions. Field traverses were conducted in August 2020 and early in the morning to take advantage of less intense and direct natural lighting conditions. The main field traverse is highlighted by the purple line through the 1 km × 1 km study area (black square) as shown in Figure 8. The purpose of the field campaign was to map the structural and lithological information in the area as well as to gather representative digital outcrop models of the unique geological units. From the regional geologic map, modified after Magnus and Easton (2015) and shown in Figure 8, much of the Gould Lake area was mapped as quartzofeldspathic gneiss, Unit 4. However, regions of chemical metasedimentary rocks (marble, Unit 1a), siliciclastic metasedimentary rocks (quartzite, Unit 3), and intrusive rocks (metagabbro, Unit 14, and syenite, Unit 16) have also been mapped in the surrounding area.

To assess the performance of the hand scanner in a geological field mapping campaign, a traverse was planned in the Gould Lake area (76.588°W, 44.460°N, southwest corner of the 1 km × 1 km area) cutting across the general northeast-striking metamorphic units as illustrated in Figure 9. The locations of the six digital outcrop models captured are highlighted throughout the field traverse by unique markers. The incorporation of 3-D digital outcrop models augmented the geological field mapping campaign by: (1) providing the full spatial context for each scanned outcrop, (2) allowing any geological in situ measurements or features (i.e., strike and dip) to be manually incorporated and displayed within the digital outcrop model, (3) the identification and documentation of morphological features on the outcrop, and (4) the real-time retention, combination, and storage of all observations within a database prior to leaving the outcrop and field site. The spatial relationships of the outcrop are also easier to visualize and interact with in the 3-D digital outcrop model as it can be zoomed, rotated, and translated, which is not possible with the 2-D images alone.

**Real-Time 3-D Digital Modeling of Quartzofeldspathic Gneiss Outcrops**

The first four outcrops scanned through the traverse match the regional geologic map with two distinct textures of quartzofeldspathic gneiss being observed. The first 3-D digital outcrop model, presented in Figure 10, is a representative outcrop of this lithological unit that shows a massive and blocky texture. The enhanced interactivity provided with the 3-D point cloud was useful as the multiple 3-D vantage points of the scan made it significantly easier to gain a sense of the 3-D block geometry, the sizes of the different blocks relative to one another, the blocks’ orientations and depths, and the dark crevasses. These 3-D features and textures of the outcrop were captured by the scanner and visualized in the outcrop model, which provided superior visualization and interpretation than photos or an inspection conducted with the naked eye.

The 3-D digital outcrop model #3, shown in Figure 11, illustrates how real-time annotations can be used to record geological features, field measurements, and physical properties. In this example, a lithological label (quartzofeldspathic gneiss), a structural feature (gneissic layering), and a strike-and-dip measurement (025/32) were annotated onto the 3-D digital outcrop model. This utility...
is beneficial, as the specific location on the outcrop where the measurement or feature was recorded can be verified within the modeling space in real-time and while still physically standing in front of the outcrop. This ability to record geological information and create a 3-D outcrop model in real-time also allows the geologist to record and tag additional comments within the outcrop model for later analysis, such as the dominant mineralogical composition of the specific gneissic layers, the magnetic nature of the outcrop, or specific sections of the outcrop that host minerals of interest. The combined utility provided by real-time, digital outcrop models and spatially tagged annotations allows the geologist to transfer geologic information obtained directly from the real-world outcrop to the outcrop model, which preserves the highest possible likeness of the outcrop, geologic observations, and spatial relationships. Overall, both the geological and spatial information can be combined and retained while in the field at the outcrop and then revisited upon returning from the field within the modeling space. This is in contrast to making connections between written notes and measurements of the outcrop and then relying on memories of the field traverse and spatial context that are not always properly located and referenced within an outcrop model. The model space can further be disseminated to others with the full information content and without requiring any additional processing.

Real-Time, 3-D Digital Modeling of Marble Outcrops

The two remaining digital outcrop models captured from the field traverse (#5 and #6) were both of marble outcrops, which comprise a different lithological unit than the quartzofeldspathic gneiss. The 3-D digital outcrop model #5, presented in Figure 12, shows a representative outcrop of this lithological unit that exhibits a massive, granular texture and differential weathering. Despite the relatively smaller size (2 m × 3 m), the spatial information gathered from the outcrop in combination with the real-time annotation ability still has several uses such as recording the degree of physical weathering, the outcrop texture, the outcrop morphology, and the locations of auxiliary minerals observed by the geologist. Specifically, this massive marble outcrop hosts a relative abundance of the auxiliary mineral graphite between the massive calcite grains. These elongated (up to 5 mm) flecks of graphite can be found making up ~5–10% of the minerals present within the outcrop. By augmenting the up-close inspection of individual minerals within the outcrop, the relative abundance of these auxiliary minerals can be mapped and annotated within the digital outcrop model. Furthermore, when a new lithological unit or texture is observed in the field, a representative digital outcrop model that captures the diagnostic features of the specific unit and/or features can be cataloged and used as a visual reminder upon leaving the field.
Several of the outcrops encountered during the Gould Lake traverse were obstructed by soil, trees, grass, moss/lichen, and/or other forms of vegetation. The 3-D digital outcrop model of marble shown in Figure 13 illustrates how despite being mostly obstructed by vegetation, a ground-level outcrop can still be scanned to capture its spatial extent. Being able to interact with the 3-D digital outcrop model makes it easier to visualize the scale and spatial information of the outcrop than trying to stitch together or flip through various 2-D images of the entire outcrop. Two-dimensional images were found to complement the 3-D digital outcrop models by highlighting specific outcrop features of interest in a higher resolution than what could have otherwise been captured by the lower resolution scanners.

DISCUSSION

Hand Scanners: A Tool for Augmenting Geological Mapping

The use of the digital hand scanners within the Gould Lake geologic mapping campaign was beneficial for augmenting the collection, retention, analysis, and communication of in situ geologic field observations and spatial relationships. The 3-D digital outcrop models collected were used to aid in organizing the spatial information and measurements observed in the field and came at a relatively low cost in terms of time (10 min for a typical 2.5 m x 7 m outcrop) and effort (no more strenuous than traditional data collection methods). The retention of the full 3-D spatial character of the outcrop in a digitized form allowed the locations of measurements and observations to be annotated directly on the outcrop in real-time, which provided a spatial context for the information gathered at the outcrop scale. The ability to exit the field with a set of digital outcrop models allowed for outcrops and observations to be quickly revisited, refreshed, and reanalyzed by directly comparing digital models. Virtual dissemination of geological data (i.e., Nesbit et al., 2020) can be beneficial under various circumstances such as inclement weather or unsafe conditions that prevent additional in situ field measurements. The implications of this include being able to better inform subsequent field traverses in new map areas and provide enhanced analysis during the review of all field observations and compilation into a geologic map and accompanying cross-section for vertical interpretations. Finally, the addition of digital outcrop models as an information product extracted from the field led to an invaluable link between the different scales of information presented. On the larger scale, the final product of a mapping campaign is a local or regional geologic map hosting small-scale individual measurements associated with specific outcrops. The digital outcrop models help to facilitate the communication of this...
multi-scale information to others who did not enter the field by establishing a link between these two scales of information. This also allows the spatial context of geologic measurements to be presented on both the outcrop model scale and the regional geologic map scale as is shown in Figure 14.

Geological map metadata typically fall into six main categories that include the map identifiers (title, authors, publication number, date, location map, and scale), the geologic map (mapped and interpreted locations of the lithologies, geologic measurement/symbols, and referenced landmarks), lithological legend (list of different lithologies within the map area), geologic symbols (outcrop, strike and dip, gneissic layering, glacial striation, and mineral occurrence), landmark symbols (towns, roads, railways, lakes, and streams), and descriptive/margin notes (introduction information, geologic setting, interpretations, and references). The geologic map of the Gould Lake area by Magnus and Easton (2015) demonstrates these metadata categories. Of these categories, three provide contextual and background information (map identifiers, landmark symbols, and descriptive notes), while three categories provide the geologic information and interpretations recorded in the field (the geologic map, lithological legend, and geologic measurements/symbols). Digital outcrop models collected in the field by hand scanners can be added as an additional, seventh category within the traditional geologic mapping framework. This additional, outcrop-scale geologic and spatial information augments the three established methods of displaying geologic information on traditional geologic maps. This digital outcrop information can be incorporated by indexing the digital outcrops gathered within the legend, adding a unique symbol used to georeference their location within the larger scale geologic map, and creating a digital link to an external database where these outcrops can be visualized and manipulated in 3-D space. By incorporating the 3-D digital outcrop models as an additional map layer, these models can augment the traditional information displayed on a field map and make the information more interactive for the end-user. An example of this approach is shown in Figure 14, where the digital outcrop model #2 is incorporated into the Gould Lake area geologic map via a specific symbol and linking node. The additional information provided by the digital outcrop models is the interactive, 3-D spatial extent that depicts where specific measurements and observations were made on the outcrop.
With a 3-D digital outcrop model built in situ, the model can be displayed and act as a spatial index for the geological information observed and gathered at the outcrop scale (i.e., strike-and-dip measurements) or for information added post-survey (i.e., radiometric dating measurements). The information and measurements that can be spatially tagged and located as nodes within the digital outcrop model can include lithology, texture, structural measurements, structural features, geotechnical measurements (rock quality designation, rock mass rating, joint roughness, joint spacing, and joint set orientation), whether the outcrop is magnetically susceptible, physical property measurements, mineral grain sizes, radiometric date measurements, abundance of auxiliary and economic minerals, high-resolution images, etc. Generally, there are more observations made at outcrops by geologists and instruments than can be physically displayed on the regional geologic map. This leads to only the critical observations (structural measurements, contacts, and faults) being incorporated on the large-scale map as authors must balance which information to display to avoid excessive clutter. These critical measurements are typically displayed adjacent to the specific outcrop where they were observed and can potentially lead to discrepancies in their exact location within the map. Also complicating this process is that outcrop locations are not evenly distributed throughout the geologic map area and can cluster, which leads to high densities of observations in relatively small areas. The rest of the information and measurements not included in the geologic map are often relegated to accompanying written reports with no direct spatial context. By breaking the digital outcrop models up into their own modeling space and placing nodes on the geologic map, all outcrop-scale observations can be linked and viewed within the geologic map.

Recently, advancements in modern digital geologic mapping, as shown by Pavlis and Mason (2017), Walker et al. (2019), and Whitmeyer et al. (2019), have allowed for the incorporation of geologic data at different scales using databases that accompany the digital geologic maps. These digital geologic map products have grown to include digital photos of the outcrop, field sketches, multiple geologic measurements (strike and dip, foliation, axial plane strike and dip, trend, and plunge), representative diagrams of geologic relationships (cross-cutting relationships, shear sense, axial plane orientation, and relative fault motion), and unique identifiers. The addition of 3-D digital outcrop models within these workflows and digital map products aid in the spatial organization of information collected at the outcrop scale as well as aid in the visualization of outcrop-scale observations.

The 3-D digital outcrop models investigated in this study also provide a direct method for georeferencing the relatively small-scale observations made on outcrops with the regional scale geologic map. Specifically, 3-D digital geological hand samples (Hudson et al., 2020) and digitized thin sections can be located and referenced within the 3-D digital outcrop models to then be incorporated as a data collection node within a large-scale geological map.

Figure 12. Three-dimensional digital outcrop model #5 of a representative marble outcrop shows the degree of physical weathering, outcrop texture, and morphology.
Figure 13. Three-dimensional digital outcrop model #6 of a large, obstructed marble outcrop covered by soil, grass, trees, and other forms of vegetation is shown.

Figure 14. The incorporation of a 3-D digital outcrop model (outcrop #2, quartzofeldspathic gneiss) linked to its location on the Gould Lake geological map provides the viewer with additional interactive, 3-D spatial information about the outcrop.
Combining digital outcrop models into a multi-scale digital visualization for geological data can improve the comprehension of geological relationships at the micro-, meso-, and macro-scales (Harvey et al., 2017). This concept has been investigated by integrating 3-D digital geological hand samples and outcrops within digitized geologic maps in a geographic information system (GIS) environment (Harvey et al., 2017; Bond and Cawood, 2021; Antoniou et al., 2020). A synthetic example that incorporates the 3-D digital outcrop models is shown in Figure 15 and illustrates how integrating multi-scale visualization techniques of various geological samples can augment the comprehension of geological relationships across all scales (kilometers–millimeters). This includes the macro-scale (plan-view geologic map of Gould Lake), outcrop-scale (digital outcrop model), meso-scale (digital geological hand sample), and the micro-scale (digitized thin section).

Future workflows can be developed to integrate the regional geologic maps with progressively smaller scales of observations that move from 3-D digital outcrop models to 3-D digital geological hand samples and interactive digitized thin sections all within a single visualization and database software. In Harvey et al. (2017), the macro-, meso-, and micro-scales of geological data were incorporated together within ArcGIS using custom widgets. More recent workflows using specialized digital field mapping software, such as StraboSpot (Walker et al., 2019) and Fieldmove (Lundmark et al., 2020), have the potential to accommodate real-time digital outcrop models collected in the field. Additionally, the workflow presented by Thiele et al. (2021) demonstrates the ability to incorporate multi-scale and multi-sensor data integrations for geologic mapping and interpretation. The overarching goal in combining 3-D digital outcrop models with these established methodologies is to provide a complete suite of multi-scale digital geological data within a fully referenced spatial and geographic context. Three-dimensional digital outcrop models are critical in linking the macro-scale interpretations presented within regional geologic maps to the meso-scale and micro-scale observations and augmenting the

Figure 15. A proof of concept demonstrates the integration of a geological map, a 3-D digital outcrop model, a 3-D digital geological hand sample, and a digitized thin section to show geological features at all scales in their respective geographical context to augment understanding of multi-scale geological relationships.
comprehension of geological observations and relationships. This strategy has the potential to retain all field data acquired and fuse them with the geological mapping database toward development of a digital geological library. Other applications where hand scanners could be beneficial include the incorporation of collected digital outcrop models within student field trips (Whitmeyer, 2012) and use as an augmented learning tool for remote and virtual education (Bond and Cawood, 2021; Cho and Clary, 2020).

**CONCLUSION**

The use of hand scanners to collect 41 digital outcrop models throughout the Gould Lake geologic mapping campaign resulted in several technical and scientific benefits. Each digital outcrop model measuring up to 2.5 m high × 7 m long took ~10 min to generate in the field (scanning and annotation) and resulted in improved retention, organization, and communication of the geological data gathered and their spatial relationships at the outcrop scale. Critically, it was found that geologic measurements, such as the strike and dip, can be located and referenced in real-time within the 3-D digital outcrop model, which links the recorded measurements and unique operator annotations with the observed geologic feature (such as gneissic layering) and explicit location on the outcrop where the measurement and feature were located. Implementing the hand scanners throughout this observation and measurement process in the field was found to improve retention of the geologic and spatial information at the outcrop scale for later analysis, mapping, and communication.

Based on the experience of scanning 41 geological outcrops with the hand scanners, several advantages were uncovered. The relatively small, lightweight hand scanners facilitated greater ease of mobility and use in the field than the bulkier and heavier digital outcrop scanners. The combine factors of scan resolution, rapid data acquisition, field mobility, and relatively low physical demand on operator endurance provide a level of utility that allows for the capture of outcrop models and the retention of data throughout an entire 8-h-long field campaign. This level of overall utility can be applied to extended field campaigns with multiple day-long excursions back-to-back without fatiguing operators. Furthermore, incorporating the hand scanners into an extended campaign can allow for the capture and review of representative geological outcrop models from previous days to better inform and plan all subsequent field traverses in advance. This was found to be particularly useful when sharing critical information between multiple field geologists who traversed different areas of the map or in communicating findings to senior geologists and supervisors who may have not entered the field to make observations. Overall, the added benefits of incorporating the 3-D digital outcrop models into geological mapping campaigns highlight the potential for using the hand scanners as an additional tool for geologists. Hand scanners are not replacing the field geologist but have been demonstrated to augment the information acquired by the geologist in the field. The digital outcrop model’s 3-D spatial information can be collected and reviewed in situ. This allows for the integration and recording of geologic information within the modeling space by the geologist, who still has direct access to the outcrop to make and record observations. These 3-D outcrop models can also be integrated with other georeferenced or draped sensor data that include terrestrial laser scanners, hyper/multi-spectral cameras, or digital photogrammetry. It should be stressed, however, that additional comparisons with more advanced technologies (terrestrial laser scanning and photogrammetry) must be conducted in a systematic manner to determine where this approach fits in the overall digital surveying of outcrops.

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