Title: Reality Capture of Hydraulics Infrastructure

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Abstract

Topographic surveys of large culvert infrastructure have typically required significant financial investments, complicated logistics, and extensive data processing, all carried out by highly trained staff. More recently, technologies such as Light Detection and Ranging (LiDAR) – which measures the distance from a sensor using the Time-of-Flight of a light pulse - and multi-camera smartphones have reduced the costs and complexity needed to obtain high-resolution, 3D models of obscure built infrastructure.

In the summer of 2022, the New Brunswick Department of Transportation and Infrastructure (NBDTI), Design Branch partnered with Modelar Technologies to evaluate the potential use of LiDAR-enabled iPhones as a tool for capturing 3D models of the interior of large culverts. The scanning software fuses multiple HD images, spatial orientation data and distance measurements from the iPhone's LiDAR sensor to construct both a 3D point cloud and a textured, triangulated 3D surface model. The quality of the resulting 3D models depends on a number of factors, including the speed at which the scanning device is moving, the sensor resolution and the lighting conditions inside the culvert.

This paper presents various aspects of this new reality capture collection system and compares the speed and cost to traditional surveying and data collection methods. The advantages (and possible drawbacks) of data collection by a wider range of staff at relatively lower cost than traditionally possible are explored. The accuracy and precision of these models are explored. Merging high-precision survey data with the mobile reality capture data and UAV 3D model to create a digital twin rendering of the asset will be shown. Additionally, the long-term goals for end-to-end processing workflows and data management are presented.

Keywords: digital twins, reality capture, scanning, SLAM, 3D modelling, structures, culverts

Introduction

Surveyors have been developing new methods of field measurements and data collection to capture details of the "real world" for centuries. Simple devices such as strings, chains, wheels, compasses, sextants, transits, levels, and theodolites were used to measure distances, angels, and height differences. Sketches and geometric calculations transformed these measurements into basic site plans. The use of digital calculators in field surveying began 40 years ago, making surveyors one of the first mobile electronic users. Structured feature coding assisted in the creation of digital line work and symbology automatically for Computer Aided Design (CAD) plans, allowing the world to be digitized.

Surveyors were the first civilian Global Positioning System (GPS) users and played a key role in its development. Establishing precise positions first took days, then hours, then minutes, seconds, and now only fractions of seconds. Boots-on-the-ground topographic surveys now use RTN GNSS (Real-time Network Global Navigation Satellite Systems) to set local geodetic control and locate certain features in seconds, dramatically reducing the time between field work and finished plan.

The reduction in time required for precise positioning was accompanied by a dramatic increase in the number of positions that can efficiently be measured. Ten years ago, making a topographic plan of a culvert site required multiple fields days and a follow-on office days. Every significant point on the site was physically measured using GPS and total stations, producing a relatively sparse CAD. Now, photogrammetric 3D modelling using cameras mounted on UAVs, and laser scanning using Light Detection and Ranging (LiDAR) sensors allow field surveyors to efficiently capture millions of position measurements. Instead of a CAD file, surveyors can produce photorealistic surface models of the visible site. These models can also be precisely oriented and scaled into the real world with locate site control captured using traditional methods. The continued upward trajectory of rapid, highly detailed data collection and processing is astounding.

The topographic survey of the culvert site mentioned above was traditionally delivered as a CAD file containing approximately 50 lines and 300 points, either plotted on paper or sent in digital form to a civil engineering team who would ultimately decide on the work that would be performed at the site. Further computations had to be performed to establish specific measurements of length, slope, diameter, area, volume, cross-section and profile. The CAD model's sparsity meant that only select, highly trained and skilled technicians and engineers new how to interpret it and use it for design decision making. The photorealistic survey models produced by reality capture systems, however, provide a complete 3D picture of a site in a form that can easily be understood without specific expertise, making site planning information accessible to a much wider audience than traditional deliverables.

While tools like photogrammetry and LiDAR sensors have revolutionized data collection, they have remained available largely to expert users with budgets large enough to acquire and run specialised hardware and software. Recently, however, consumer-grade smartphones have become more powerful and have begun to include advanced positioning algorithms and LiDAR sensors, making them possible platforms for 3D reality capture. Furthermore, smartphones are able to operate in constrained environments, such as the interior of hydraulic assets such as culverts. Space in these environments is very limited, and conditions are often obscured, with rough and slippery terrain, making them difficult or impossible to survey with UAV flights. Smartphones are also easy to use, have lower capital costs than typical reality capture systems, and are usually already part of every large organization's IT portfolio, lowering the barriers to adoption.

If the 3D models produced that can be produced using smartphones are fit-for-purpose, it would allow for a dramatic reduction in the costs and complexity for obtaining a high-resolution, 3D datasets of built infrastructure. It would also allow a much wider range of staff to capture and catalog site conditions than ever before. For these reasons the New Brunswick Department of Transportation and Infrastructure (NBDTI), Design Branch investigated the use of low-cost smartphone-based reality capture systems as a means of capturing detailed 3D models of the interior of large culverts.

Methodology

To evaluate the suitability of smartphones for reality capture, NBDTI Design Branch partnered with Modelar Technologies, which develops the Modelar 3D scanning software for mobile devices. Initial field trials took place in the fall of 2021, during which the interiors of three culverts were surveyed by Modelar Technologies. A more comprehensive field trial was conducted in the summer of 2022, during which engineering students from the University of New Brunswick employed by NBDTI captured over 130 scans of 30 different culverts.

Software

Modelar uses iPhone Pro and iPad Pro models with the integrated LiDAR sensor. The software consists of an iOS field collection app that captures both 3D point clouds and textured 3D triangulated meshes, and a cloud-based data management and visualization system to which the app connects over a standard Internet connection and uploads scan data.

When performing a scan, the app captures RGB images from the device's camera and depth maps from the device's integrated LiDAR sensor, and continuously updates the device position and orientation in 3D space using the onboard SLAM system. Each depth map is filtered to remove measurements considered low confidence by the underlying hardware, then combined with the device position and orientation to generate a set of 3D point positions. These are fused into a multi-resolution hierarchical 3D point cloud and a triangulated 3D mesh, both in real time, then rendered over the camera feed to provide an augmented real-time view that clearly shows which portions of a structure have been captured while scanning.

The real-time augmented view can also be used to create point and photo annotations while scanning. This allows specific features of interest (e.g. ground control markers) or artifacts (e.g. cracks in concrete facing) to be identified and highlighted for later review. Both point and photo annotations are tied to 3D positions and can be visualized alongside the 3D model.

When scanning is complete, the 3D point cloud is gridded at high resolution and merged with the RGB images to create a textured 3D mesh. All processing is carried out on device, allowing a complete picture of the scanned area to be determined even on remote sites without a network connection. Once a network connection is established the Modelar app can upload the entire scan – including all scan data, point and photo annotations, and the textured mesh generated afterwards - to the cloud-based storage and management system. The cloud system processes both the 3D point cloud and textured mesh into structures that are suitable for visualization on the web.

Scanning process

The Modelar app was deployed on iPhone Pro 13 smartphones with 256GB of storage space and LiDAR sensors. Because the maximum range of the LiDAR sensor is 5m and culvert interiors are typically opaque, limiting the distance at which images could be captured, the devices were mounted on an extensible monopod that allowed surveyors to move the device closer to objects of interest when necessary. A consumer-grade LED illumination panel was attached to the monopod to provide consistent lighting that improves visibility inside the culvert.

Prior to each scan, operators performed a pre-walk, during which they investigated the confined environment. This allowed safe determination of a secure footing path around navigation and obstructions without focusing on data capture, which was essential for personal safety. The pre-walk also allowed operators to develop an environment-specific step-by-step protocol for conducting a scan, and identify features of interest such as areas of structural failure, damage, and cracking.

As part of the pre-walk, operators also identified locations for Ground Control Points (GCPs) on the culvert walls at its entrance, midpoint and exit. These were used to georeference and correct the scan during post-processing. GCPs were marked using a reflective bullseye target or a concrete nail with bright paint. In some cases, uniquely distinguishable visual features such as a crack or seam were used and identified using a photograph.

Operators then returned to the culvert entrance and began scanning. The device was moved in a circular motion to capture unobstructed images of the culvert's walls and ceiling. Periodically, observers paused the scanning process to reorient themselves and use the real-time display to validate that complete scan coverage was obtained. Ground Control Points (GCP) and features of interest identified during the pre-walk were annotated as either point or photo annotations as they were encountered during the scan.

Depending on the length and width of the culvert, a typical culvert scan takes approximately 45 minutes to an hour to complete from the point of entry to the end of the exit and 45 minutes to an hour to travel back to the point of entry. Consistent lighting of the subject matter was found to be a major consideration in terms of scan quality model. Scans were typically conducted on days when overhead lighting did not cause glare or reflections on the water on the culvert floor.

Post-processing

Once the scan was complete, operators computed a high-resolution textured 3D model on site to validate that they had obtained complete coverage of all desired areas. In cases where coverage was incomplete, a second pass was performed. Survey teams with high-precision total stations then measured the location of the GCP markers left by the scan operators with millimetre precision, often several days after the scan was complete.

All mobile scanning systems exhibit drift - errors in the estimated camera position and orientation that may increase over time. To address this issue, Modelar developed a robust post-processing correction algorithm that associates the GCP points tagged as point annotations with the high-precision coordinates captured by the survey teams. The algorithm uses a robust least-squares-based algorithm to adjust the scan path generated by the app's SLAM system to minimize the distance between the GCPs and the high-precision coordinates. Once this optimization is performed, the 3D point cloud and textured mesh are recomputed, as are the locations of all point and photo annotations captured while scanning. Since the GCP positions are georeferenced, the resulting scan is also fully georeferenced and can be uploaded to the cloud-based management system and displayed on a map.

Results

The new work breakdown is as follows:

- Geodetic Site control, 10-50mins.
- Traditional topo survey 500 points, and 1-2hrs.
- UAV flight 30mins.
- Interior scan with iPhone 2hrs.
- Drive back to the office 1-4hrs
- 3D model is ready for a quality control check. 1hr
- Shared with the designers at the end of the workday.

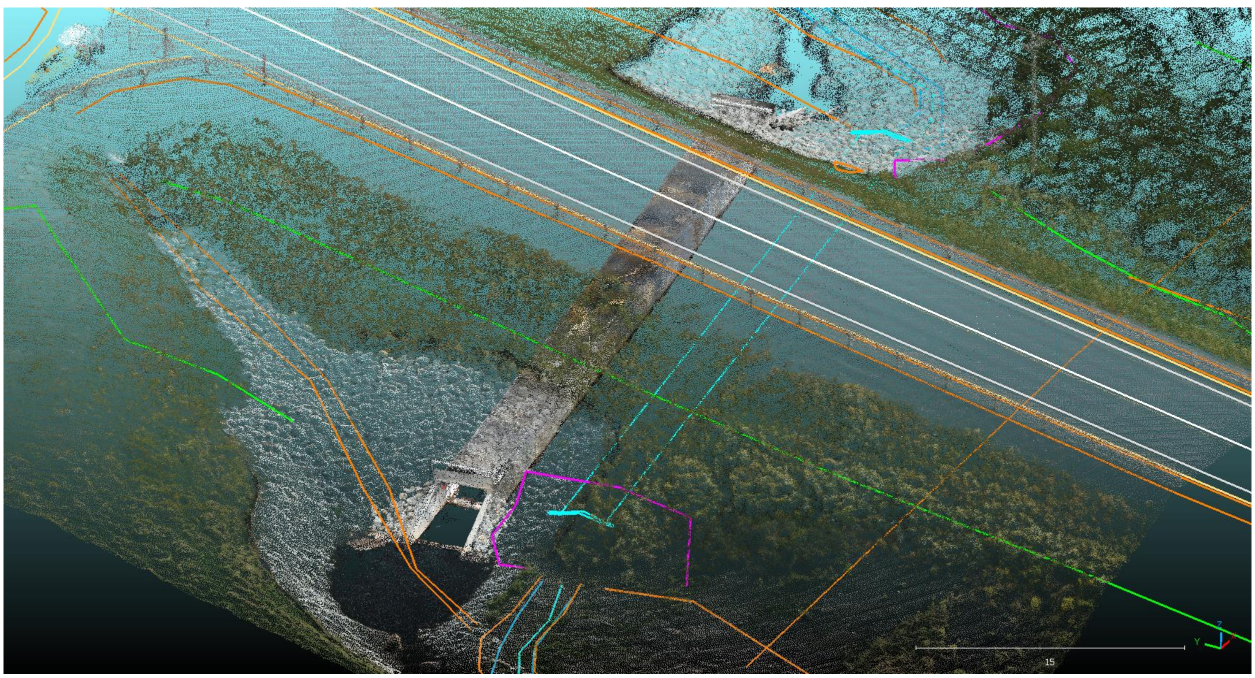

Figure 1. As-built Reality Capture with Vector CAD file of Cricket Cover Culvert No 1 and surrounding area.

Today a culvert survey takes about 2-4hrs of field work and yields a true reality capture of the site. It is in full colour and comprises millions of measured points. It can be understood by almost everyone. No interpretation is required to comprehend what it is. You see what is. It is a data rich deliverable. It is reality in your office. This type of survey has brough the user to the field without the threat of black flies, mosquitoes, ticks, hog weed, muddy boots, claustrophobia, sciatica, heat exhaustion or cold hands and feet. Thank you, geomatics, for bringing the build world reality to our offices.

Conclusions

This is only the birth story of the digital twin. This new entity can now start to grow. Addition information can be brought into this new digital twin model. Thanks to provincial geomatics agencies there is an exacting LiDAR terrain model that surrounds the asset. Precise watershed drainage and the entire water course hydraulic morphology is available. The resultant terrain model is now a billion positions in full technicolor. A digital twin is growing.

Where the challenge of the traditional asset survey was that of sparce data, this digital twin model may have too much data, too much detail. It is now big data. But we are in the right time and the right place.

Filters, surface smoothers, automated feature extraction, automated computations and now AI can automate the analysis, understanding, and management of the asset. Automated road mark extraction, automated pole and road sign extraction, automated crack detection are existing feature extraction algorithms, and the list will continue to grow.

Now integrate GIS layers. The rich spatial data warehouse information – specific control section data of pavement history, traffic counts, winter operations schedules, environmental data such as wetland delineation, property information (boundaries and ownership), jurisdictional information, and land classification. Integrate the Asset Management database that has the entire inspection history of the structure with historical records, photos, and plans. Bring in associated data like archaeological investigations, historical orthometric photos pairs, environmental assessments, geotechnical bore holes, and associated permits. Realtime sensors on the structural asset that are connected via IoT (Internet of Things) will stream conditional information.

There is a confluence of technologies for this new data model which allows these gigantic datasets to be served up via cloud services specifically designed for mega/giga sized files. The computing power does not have to reside with the user's laptop/desktop. The heavy lifting is done by the hosting server system. The user connects to the 3D reality model and conducts their work seamlessly using the hosted datasets and services. AI will assist in managing theses virtual replicas. AI simulations will yield deeper insights of the real-world conditions of build world. It has become a deeply connected data model of the asset. Everything, everywhere, all at once. That's a digital twin, but the plot much easier to follow.