Photogrammetric Modelling of the Grand Falls Generating Station Intake Tunnel

by

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Abstract

The Grand Falls Generating Station is located in Grand Falls New Brunswick on the Saint John River. The generating station is typically shut down once every four years for only a few days to perform visual inspections and maintenance of the intake tunnel. Estimates of the size and location of erosion-induced cavities are documented in reports and spreadsheets, which are then used to plan and prioritize maintenance. Interpreting inspections in preparation for maintenance is challenging given the size of the intake tunnel, the subjectivity and selectiveness of the inspections, and the difficulty in linking the spatial evolution of erosion between subsequent inspections.

A photogrammetric inspection system was developed to document the visual and spatial condition of the Grand Falls intake tunnel in a 3D model. A robotic data acquisition system incorporating microcontrollers, wireless technology, and photography equipment including lighting was designed, fabricated, tested, and refined to facilitate data capture. Approximately 5,000 images were taken of the 822 m concrete-lined section of the Grand Falls intake tunnel during a two-week scheduled shutdown for maintenance and repairs. The images were processed and combined with traditional surveying to generate an accurate and high-resolution 3D model. A custom interface was designed to visualize and interact with the model and incorporates an inspection-specific tool set. The Grand Falls intake tunnel model will enable more informed decisions on how to manage the intake tunnel and could lead to reduced lifecycle spending, reduced risk of failure, and extended service life. NB Power senior management are enthusiastic about the results of the research and see significant value in using the photogrammetric inspection system at a variety of NB Power facilities. An additional pilot study was completed in Unit #5 at the Mactaquac Generating Station.
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List of Abbreviations and Acronyms

2D  Two dimensional
3D  Three dimensional
AAR  Alkali aggregate reaction
BIM  Building information model
CCW  Counter clockwise
CEATI  Centre for Energy Advancement through Technological Innovation
CW  Clockwise
DIC  Digital image correlation
DSLR  Digital single lens reflex
Grand Falls  Grand Falls Generating Station
GSD  Ground sampling distance
ISO  Imaging sensor sensitivity
IMU  Inertial measurement unit
LiDAR  Light detection and ranging
LVDT  Linear variable differential transformer
Mactaquac  Mactaquac Generating Station
NB Power  New Brunswick Power
POI  Point of interest
SFM  Structure from motion
SLAM  Simultaneous localization and mapping
RMS  Root mean square
TIA  Tunnel inspection assistant
UAV  Unoccupied aerial vehicle
UNB  University of New Brunswick
1 Introduction

The Grand Falls Hydroelectric Generating Station (herein referred to as Grand Falls) was constructed in the late 1920s and is operated by New Brunswick Power (NB Power). An intake tunnel approximately 921 m in length diverts water from the Saint John River, and travels beneath the city to a power house with four Francis turbines that have a total capacity of 66 MW (H.G. Acres & Co Limited 1928, (Wikipedia Contributors 2017a). The tunnel consists of four main sections: 1) a steel-lined horizontal intake and vertical riser shaft, 2) a horizontal non-reinforced-concrete-lined section connecting the intake to the distributor, 3) a steel-lined section including the distributor and penstocks, and 4) steel scroll cases and wicket gates. This research focuses on section 2, which is 822 m long and 7.5 m in diameter. Figure 1 provides a plan view of the generating station intake tunnel overlaid on a Google Earth aerial image. Figure 2 is a drawing of the intake tunnel that provides details on the sections.

Figure 1 – Sketch of the Grand Falls Generating Station intake tunnel (Google Earth 2018)
Figure 2 – Drawing of the Grand Falls intake tunnel (H.G. Acres & Co Limited 1928)
Inspection and maintenance of the tunnel is performed on a four-year cycle, which includes taking the generating units off-line, securing the switch yard, shutting down the station and dewatering the tunnel (New Brunswick Power Corporation 2004). This process requires a few days and the shutdown typically lasts for only a few days. The inspection is primarily visual-based and observations are made from the tunnel invert, which is the base of the tunnel. Both visual and spatial information is collected during the inspection. Inspection reports from 1998, 2004, 2007, 2008 and 2012 are available and documented in spreadsheet form, including the longitudinal and clock location, size, and remarks on the deterioration (New Brunswick Power Corporation 2004, SNC-Lavalin Inc 2007, 2008, 2013). The style and information documented does change slightly from year to year. In 2004 a sketch was provided for some of the defects and is a convenient visual reference. Mobile staging was set up during the 2007 inspection to allow more detailed observation of select locations, as well as hammer sounding to identify locations with weak bonding between the concrete and bedrock, and hollow spots. Pictures of critical areas were taken during the inspection, although they are difficult to interpret as their location in the tunnel is unknown. The quality of the images is also poor due to the insufficient light provided by the onboard camera flash. The inspection report from 2004 highlights the importance of photographs to provide a visual reference as well as the need for better photographs. The types of deterioration documented in the spreadsheet include holes, cracks, leaks through cracks and construction joints, deterioration of the concrete surface, spalling, raveling, missing sections of concrete, deterioration of patches, and aggregate exposure. Figure 3 is a sample of the spreadsheet from the 2012 inspection and includes a side by side comparison of the inspection completed in 2007. Figure 4 is a photograph of a hole in the concrete liner taken during the 2004 inspection.
Figure 3 – Sample of the defect spreadsheet from the 2012 inspection (SNC-Lavalin Inc 2013)
Figure 4 – Photograph of a hole in the concrete liner from the 2004 inspection (NB Power 2004)
The purpose of inspecting the intake tunnel is to assess the condition of the tunnel and plan rehabilitation to be performed during subsequent inspections. The text-based inspection reports do not facilitate visualization of deterioration throughout the intake tunnel. Interpreting inspections in preparation for maintenance is challenging given the size of the intake tunnel, the subjectivity and selectiveness of the inspections, and the difficulty in linking the spatial evolution of erosion between subsequent inspections. Delivering the inspection in a visual format would be more intuitive for visualizing deterioration and planning rehabilitation.

1.1 Significance
There is a significant opportunity cost associated with shutting down the generating station to inspect the tunnel. The shutdown requires purchasing the electricity that would have been produced by the station from another distributor. The cost of purchasing electricity to make up for the loss of electricity generation during the shutdown is approximately $38,000 per day (Hanscom 2017a). This cost considers the potential generation under the anticipated flow conditions during August, which is typically when the shutdown occurs.

1.2 Problem Statement
The traditional inspection does not facilitate visualization of deterioration and inadequately supports rehabilitation planning. Three dimensional (3D) modelling techniques provide an opportunity to accurately document the visual and spatial condition of the Grand Falls intake tunnel in an intuitive visual format that better supports rehabilitation planning. This format would document the entire concrete-lined section of the tunnel, rather than only the items identified by the inspector, and would allow additional specialized experts to interpret the condition of the tunnel. Three overarching research questions arise from the main elements
of 3D modelling, which are data acquisition, data modelling, and model delivery. The key research questions are:

- What equipment and processes are required to document the visual and spatial conditions of the entire concrete-lined section of the tunnel?
- How could the visual and spatial data be processed to create 3D models?
- How could an interface be designed and assembled to navigate the 3D models delivered to facilitate visualization and support rehabilitation planning?

1.3 Goal

The goal of this study is to develop an inspection system to document the visual and spatial conditions of the entire concrete-lined section of the Grand Falls intake tunnel. The inspection system will integrate high resolution imagery and high accuracy spatial data in an intuitive interface to facilitate visualization of deterioration and rehabilitation planning.

The objectives of this study are:

- To develop a data acquisition system and collect visual and spatial data of the entire concrete-lined section of the Grand Falls intake tunnel.
- To process the visual and spatial data and generate 3D models of the Grand Falls intake tunnel.
- To develop a custom interface with an inspection-specific tool set to interact with the 3D models.
1.4 Scope

Data capture technology was assessed including mobile LiDAR, stationary LiDAR, and photogrammetry. A photogrammetric inspection system was developed in collaboration with NB Power to document the visual and spatial condition of the Grand Falls Hydroelectric Generating Station intake tunnel in a 3D model. The photogrammetric inspection system consists of three main components: data acquisition, data modelling, and model delivery. A robotic data acquisition system was designed and fabricated to facilitate positioning the camera in an efficient manner. The photogrammetric inspection was conducted from August 21, 2017, to August 31, 2017, and focused on the 822 m concrete-lined section of the tunnel. Three data sets were collected with the camera at various heights perpendicular to the surface of the tunnel: the entire concrete-lined section of the tunnel was captured with the camera at a height of 5 m, a 30 m section of the tunnel was captured with the camera at a height of 3 m, and a 8 m section was captured where repairs were completed with the camera at a height of 5 m. The 3D models were generated with a process relying on Agisoft Photoscan (Agisoft 2018a). The models were delivered in a custom interface that was developed to facilitate visualization and navigation of the models and also provide an inspection-specific tool set. The success of the Grand Falls inspection generated interest with other parties at NB Power and led to applying the photogrammetric inspection system at the Mactaquac Generating Station to document the discharge ring and draft tube of Unit #5.
1.5 Readers’ Guide

For convenient reference, this thesis is organized as follows:

- Chapter 2 reviews the current state of the art in hydroelectric tunnel inspections. Technology used to capture visual and spatial data to generate 3D models is also reviewed to assess its potential for inspecting the Grand Falls intake tunnel. The technology reviewed includes stationary LiDAR, mobile LiDAR, and photogrammetry. Unoccupied aerial vehicles (UAVs) are also reviewed as a mechanism for capturing LiDAR and photogrammetry data.

- Chapter 3 describes the challenges of planning rehabilitation of the Grand Falls intake tunnel using the results of the traditional inspection. The objectives of an improved inspection system are also identified and serve as the basis for selecting a capture technology.

- Chapter 4 describes the data acquisition system design and the process of capturing the Grand Falls intake tunnel data. The selection of photogrammetric parameters is discussed, as well as the main components of the data acquisition system and automation used to facilitate data capture.

- Chapter 5 describes the processing steps to generate the 3D models of the Grand Falls intake tunnel, as well as the development of the custom interface.

- Chapter 6 discusses the practical application of the generated model. A comparison of the traditional and photogrammetric inspections is presented.

- Chapter 7 discusses the application of the photogrammetric inspection system at the Mactaquac Generating Station. The visual and spatial
condition of the discharge ring and draft tube of Unit #5 was documented with the photogrammetric inspection system. The motivation, data acquisition, data modelling, model delivery, and practical application of the models are discussed.

- Chapter 8 provides conclusions of the research study and recommendations on how researchers should build on this research, how NB Power should use the developed technology, and how industry should prepare for adopting the technology.
2 Literature Review

The literature review is divided into two sections. The first section assesses the state of the art in hydroelectric tunnel inspections and forms the basis for identifying improvements to NB Power’s traditional inspection. The literature contains a significant number of articles related to tunnel inspections, although articles specific to hydroelectric tunnels are sparse and consist mainly of case studies. Several articles on underwater inspections were also found, although the scope of this research is limited to tunnels that are dewatered prior to inspection.

The second section of the literature review identifies rapidly evolving 3D technologies capable of capturing, modelling and visualizing high resolution visual and spatial data in a 3D model. The review is focused on the technology used for civil infrastructure inspection and is categorized by capture technology, as it is the prominent theme in the reviewed articles. Capturing data is only one component of inspecting and managing infrastructure, as indicated by the general asset management framework displayed in Figure 5. The framework consists of collecting data, processing and analyzing the data, developing deterioration models to predict the future condition of the asset, as well as making and implementing decisions on how to manage the asset. Capture technology falls within the data acquisition and data processing and analysis steps.

2.1 Hydroelectric Tunnel Inspection

2.1.1 Current Practice

Wang and Lee (2013) assessed hydroelectric tunnel inspection and maintenance case studies from Taiwan. Several challenges associated with inspecting hydraulic tunnels, as well as typical anomalies found during inspections, are identified and
form the basis of considerations proposed for design improvements to facilitate inspection and maintenance on future tunnels.

Challenges of inspection identified include inaccessibility and difficulty of passage, insufficient lighting and ventilation, lack of location referencing, and visual obstruction of the lining. Major anomalies found in hydraulic tunnels include lining cracks, concrete spalling, concrete breaking away, concrete peeling, lining displacement, concrete honeycombing, and deformation.

A case study of the Stanley Canyon Tunnel also highlights the effort required to inspect hydroelectric tunnels. The tunnel is approximately 4.9 km long and 3 m in diameter, and transports water from the Rampart Reservoir to the Tesla Hydro Power Plant north of Colorado Springs, Colorado. The tunnel is inspected every ten years; the most recent inspection was completed in 2015 by Ganse et al. (2016). The majority of the tunnel is lined with reinforced and non-reinforced
concrete. A 996 m section at the hydro plant end is lined with epoxy-coated steel. The case study emphasizes the effort involved with inspecting a hydraulic tunnel and details the complex process of draining the tunnel, and the safety requirements including isolating the structure, safety training, emergency rescue plans, ventilation, and communication.

Visual observations and non-destructive testing were performed during the inspection. A series of custom applications were developed to document the visual observations and transfer them to a desktop database. Visual observations were documented using a modified version of the National Association of Sewer Service Companies Pipe Line Assessment Certification Program coding system. The system documents the date and time of inspection, as well as the type, station, clock location when facing downstream, and the size of defects. Defects were plotted in a two dimensional (2D) figure to visualize the location of deterioration. The figures do not provide visualization of specific deterioration, which would be useful for interpreting deterioration and implementing repairs and also performing comparisons with subsequent inspections. Nonetheless, the authors note that using a standardized inspection system will facilitate comparisons among inspections (Ganse et al. 2016).

The El Monte pipeline is a 21 km long network of reinforced-concrete and steel pipelines ranging from 0.46 m to 1.83 in diameter that provide raw water to the Alvarado water treatment plant in San Diego, California. Shelton et al. (2016) inspected the El Monte pipeline in 2014 and 2015. The inspection consisted of visual observations, measurements, and sound testing. Few details are reported on the results and usefulness of the inspection other than to indicate that the field data was recorded using asset management software, although the inspection
planning process is well documented. Planning included: determining how and where to enter and exit, navigating throughout the pipeline, and maintaining safety. Safety included isolating the pipeline from other systems, using fall protection equipment, taking precautions on steep slopes and in the vicinity of deep water, identifying dedicated confined-space certified personnel, installing ventilation to ensure air quality, implementing communication and first aid protocols, and planning transportation in the pipeline.

2.1.2 Recent Advances

The rapid evolution of unoccupied aerial vehicles (UAVs) has made them accessible to inexperienced pilots and has facilitated their use for data acquisition in a variety of industries (Ferguson 2014). Several payloads are common depending on the data required and include LiDAR, RGB cameras, and thermal cameras. UAV’s are particularly well suited to data acquisition in inaccessible or difficult to reach areas. The recent adoption of UAV technology in hydroelectric tunnel inspections, as seen in Mohta et al. (2016), is anticipated to grow given the strengths of the technology.

Mohta et al. (2016) designed an autonomous UAV for inspecting penstocks with the goal of increasing safety and reducing inspection effort and cost. The main contribution of the authors is the positioning system, which cannot rely on GPS as is done with UAVs in outdoor environments. The lack of GPS makes indoor positioning challenging. The authors position the UAV using a combination of an RGB camera and LED lighting, an inertial measurement unit (IMU), LiDAR sensors, and a map of the tunnel. The accuracy of the positioning system is approximately 2.5% of the distance from the start position.
The results of the inspection are 360 degree panoramic images of the tunnel projected onto the provided map, and a low resolution LiDAR point cloud. Visual quality is low given the resolution of the VGA cameras. Inspecting large areas may be challenging due to the limited flight time of 8 minutes. The requirement for a map of the tunnel beforehand and the lack of measurement data are also significant limitations. The potential benefits of this technology far outweigh the current limitations, which will likely evolve quickly and include high resolution visual and spatial data.

2.2 3D Technology in Civil Infrastructure Inspection

Several 3D technologies that could be adopted for hydroelectric tunnel inspections were identified. The literature on 3D technologies is categorized based on the capture technology used as it is the predominant topic of the articles. Capture technologies include LiDAR, structure from motion (SFM) photogrammetry, and digital image correlation. These are all forms of non-contact remote sensing technologies. A section of literature on the use of UAVs for inspection purposes is also presented.

An overview and assessment of non-contact remote sensing technologies and their suitability in assessing the condition of bridges is provided by Vaghefi et al. (2012). Many of the technologies assessed are either not suitable for use in a tunnel (e.g. airborne imagery) or do not provide visual and spatial data (e.g. ground penetrating radar). Nonetheless, their review provides a basis for investigating potential technologies. LiDAR in combination with photography and photogrammetry were reviewed and scored very high in the assessment for detecting and identifying surface distresses visually and spatially, which are critical for inspecting hydroelectric tunnels. The review focused primarily on the
capture technology and not on the processing required or interfaces for visualizing the captured data.

2.2.1 LiDAR

Wang et al. (2014) provide a brief overview of laser scanners and their use in scanning tunnels. Laser scanners have proved to be an efficient tool for monitoring tunnels during excavation for structural integrity, for volume estimates, as well as for documenting their as-built condition to assess deformation over the long-term, and for feature extraction to compare with design. Laser scanners typically have accuracies at the millimeter level, which can be improved with statistical techniques. In comparison with traditional methods, LiDAR is quicker and safer as work can be completed at a distance from hazardous areas.

One of the first uses of LiDAR to measure deformations in a tunnel was performed by van Gosliga et al. (2006). The motivation to use LiDAR for deformation measurement was to provide increased points of measurement with minimal additional effort compared to traditional surveying. A LiDAR scan of a transportation tunnel was compared to the as-designed ideal cylindrical model. A second LiDAR scan was completed with artificial deformations introduced for comparison with the first LiDAR scan. The comparison was able to detect deformations larger than 15 mm. No specific interface was used for visualizing the LiDAR data or making comparisons between datasets.

Laser scanners have evolved rapidly since their first introduction, capturing more data in less time and creating greater post-processing demands. Workflows have evolved as well to improve the accuracy of the models. The accuracy of laser scans is largely impacted by the design of the survey, which is often neglected.
Pejić (2013) developed a methodology to optimise scanning parameters and design the control survey to ensure accurate results. Accurate results in a tunnel environment are challenging given the geometry. Errors accumulate along the length of the tunnel as individual scans are registered into a global model. Reducing error requires consideration of the incident angle and scan resolution, which is largely controlled by the scan spacing. Scan spacing is often in competition with the time or effort available for the project. Reducing the incident angle and increasing resolution requires reducing scan spacing, hence increasing field time.

The proposed methodology demonstrates that scanning parameters and a survey control network can be designed to achieve a desired accuracy. Pejić (2013) also notes the need for improved modelling knowledge, as well as 3D modelling hardware and software in order to work with models. Transforming the 3D models into a traditional 2D format, such as drawings, is recommended for presentation.

A virtual reality visualization tool was developed by Chmelina et al. (2012) to interpret LiDAR scans, as well as other types of data, acquired from a tunnel. LiDAR scanning was completed using a custom multi sensor scanning system consisting of a 3D laser scanner, total station, and digital camera on a mobile cart. Incorporating all three sensors facilitated georeferencing the scans as well as visual documentation. The authors note that the visualization tool enables users to gain rapid understanding of the data.

Traditional terrestrial LiDAR has been performed with stationary scanners. Mobile scanners are now commercially available and use simultaneous localization and mapping (SLAM) algorithms to generate a point cloud while also positioning
the scanner in the modeled environment (GeoSLAM 2017). Data can be captured at a walking pace with an accuracy and resolution on the order of several centimeters. The technology is being adopted in several industries including surveying, engineering, mining, forestry, and facilities and asset management.

### 2.2.2 Structure From Motion

Structure from motion (SFM) is a photogrammetric method of extracting geometry from overlapping images taken from different locations. The images are processed to generate a 3D point cloud. Several algorithms have been developed to automate this process, although they are outside the scope of this research. The current state of the art and potential areas of future research are presented by Fathi et al. (2015).

A key advantage of SFM is the collection of high resolution imagery that can be incorporated into the resulting 3D model. SFM has gained significant attention with the rapid evolution and use of UAVs as they are commonly used to capture high resolution imagery, which is then post processed to generate 3D point clouds for spatial assessment.

A challenge with SFM is to maintain a high level of detail as the overall scale of the model increases. Khaloo and Lattanzi (2016) use a hierarchical approach to generate large scale models that retain submillimetre details. Multiple imaging networks are used to capture images of a scene with increasing levels of detail. Image networks are processed to generate 3D point clouds independently, which are then merged into a global model. The result is a large-scale model that is denser, has a higher resolution and less noise than LiDAR, and is capable of maintaining a resolution of 0.1 mm in areas of interest. These high-resolution
models are suitable for detailed structural inspections performed offsite. The approach requires well planned data acquisition to ensure sufficient overlap and transition between image networks so that each can be merged into a global model.

Photogrammetry and LiDAR have gained popularity for visual and spatial documentation as they are capable of quickly and accurately documenting large areas. There are visual and spatial differences between photogrammetry and LiDAR, although spatial accuracy is the common goal. LiDAR is capable of millimeter accuracy and photogrammetry is typically considered to be less accurate, approximately an order of magnitude lower than LiDAR (Khaloo and Lattanzi 2016). The accuracy of photogrammetry is highly dependent on several factors, including:

1) the quality of the camera used (such as the optical precision of the lens and the quantity of pixels in forming a digital image),
2) the quality of the photos taken (such as the clarity, the lighting, and the contrast of the picture; the shooting distance between the object and the camera) and
3) the functionality of the photoprocessing software applied (e.g., the calibration of a camera, resulting in the determination of the camera’s internal parameters for photogrammetry computing.) (Dai and Lu 2010).

The potential accuracy of photogrammetry is regarded as one to three times the sampling size of a pixel, also known as the ground sampling distance (GSD) (Kung et al. 2011, Barry and Coakley 2013, Vautherin et al. 2016)

Dai and Lu (2010) assessed accuracy of SFM by comparing 67 measurements of building components obtained from an SFM model to those obtained with a tape measure. The goal was to develop a statistical method of assessing the accuracy of SFM for use in the construction industry. They employ the “95% limits of agreement” statistical analysis after illustrating that regression and correlation techniques are not suitable given the contrast in size between the measurements
and the errors, and also that the two sets of measurements are taken on the same object. The analysis of the “95% limits of agreement” using a 95% confidence interval indicated that the SFM measurements are within -15.30 and +11.39 mm of the measurements obtained with the tape measure. This accuracy is suitable for engineering purposes, although as noted by the authors there are numerous factors that affect the accuracy of SFM models that need to be considered.

Charbonnier et al. (2013) used a photogrammetric system to inspect the walls of a 475 m stone tunnel in a canal. The system was built on a floating barge and consisted of several stereo and panoramic cameras, and artificial lighting to obtain proper exposure (Albert et al. 2013). The panoramic images provided a visualization of sections of the canal, and measurements were possible within stereo pairs of images. Images from the cameras were also used to build the 3D photogrammetric model of the canal. The accuracy of the photogrammetric model was assessed by comparing it to a LiDAR scan of the tunnel. The accuracy of the photogrammetry model was approximately 5 cm.

### 2.2.3 Digital Image Correlation

Digital image correlation (DIC) is an image-based measurement technique based on pattern recognition and tracking, and provides full field displacement and strains. Measurements are possible anywhere within the field of view of the camera. A speckled pattern is typically applied to the object of interest to provide visual texture for the tracking algorithms. Ramos et al. (2015) investigated the behaviour of reinforced concrete walls infilled with masonry using DIC in a laboratory setting. Measuring displacement and strains provided a better understanding of the failure modes of the walls during seismic events. Measurements obtained by DIC were validated with linear variable differential
transformers (LVDTs). The DIC measurements strongly agreed with those obtained with the LVDTs.

MacNish et al. (2015) also report high accuracies with DIC and have been able to reproduce accuracies of 1/100th of a pixel using simulated data. DIC has several limitations that make its use challenging in the field. MacNish et al. (2015) are investigating methods to overcome the need for an applied speckle pattern, which is not feasible for a large structure in the field. They note improved performance with their algorithm, which implements a dynamic subset selection to optimize the subset size and incorporates colour data instead of the traditional grayscale images used for DIC. They have also developed algorithms to improve the technique's ability to perform when discontinuities are introduced during deformation.

DIC has the potential to obtain very high spatial accuracy, although the need for an applied speckle pattern, as well as maintaining the camera in a fixed location, renders it unsuitable for generating 3D models of tunnels.

2.2.4 Unoccupied Aerial Vehicles

UAVs have become an increasingly popular method of acquiring data, and in particular for capturing digital images either for visual use or to be further processed using SFM to create 3D models. Ferguson (2014) notes a rapid increase in the publications associated with UAVs beginning in 2011 in a variety of industries.

Using a UAV to capture digital images for assessment of infrastructure condition may be more suitable than traditional methods in some circumstances, such as for
preliminary assessments or more frequent assessments. Gillins et al. (2016) used a drone for a bridge inspection and found that the imagery provided comparable information to what would be identified at arm's length during a visual inspection. More frequent inspections were possible given the lower cost of inspection. Inspections with a drone were also noted to be much safer than traditional inspection methods, which typically require an inspector to work at height on scaffolding.

Liu et al. (2016) also noted the reduced cost and safety benefits achieved with the use of a drone for inspection. A construction project that was abandoned for ten years required an inspection of a curtain wall before construction could resume. A drone was selected primarily for the reduction in costs compared to scaffolding. Their primary challenge was delivering images captured by the drone in a convenient manner that identified where the images were taken and what portion of the wall was captured by a particular image. Their solution was to embed the images in a 3D building information model (BIM) as reference points that could be clicked to open the image. The interface locates the images in 3D space in relation to the curtain wall, although it does not appear to indicate the extents of the image or the direction from which it was taken.

Liu et al. (2016) also generated a 3D point cloud from the images using SFM and compared it to a point cloud generated with a laser scanner, although discussion on the comparison was limited. A key advantage of SFM is the capture of high resolution images and the ability to post process them to generate an accurate 3D point cloud for spatial assessment.
2.3 Photogrammetric Processing

Generating a 3D model requires processing the images through a series of steps with SFM software. The variety of commercial software options that are available makes selecting a package challenging. Two key differentiators between them are the level of control provided to the user and the ease of use. Some software is also tailored to a specific application, such as capture from UAVs, and provides additional relevant features and deliverables. SFM software is largely automated, although developing an automated process that produces desirable results requires careful attention at each processing step. Four major steps that require user input were identified within the SFM workflow and are described in the following subsections.

2.3.1 Image Alignment

Aligning images is the first step in SFM processing. The output from this step is a low density point cloud referred to as a sparse point cloud. Image alignment requires generating keypoints in each image that are then matched in overlapping images. Triangulation is used to determine the 3D coordinates of the keypoints and cameras. A sparse point cloud is the aggregation of matched keypoints.

The quality of the alignment is influenced by an image scaling factor that modifies the original size of the image. Reducing the size of the image reduces processing time at the expense of reduced alignment accuracy. The error of the image alignment process is described by the root mean square (RMS) reprojection error of all keypoints. (Agisoft 2018b) describes the reprojection error as “...the distance between the point on the image where a reconstructed 3D point can be projected and the original projection of that 3D point detected on the photo...” (Figure 6). The reprojection error of the sparse point cloud can be reduced by removing
keypoints with a high reprojection error and optimizing the position of the cameras based on the remaining keypoints. “High reprojection error usually indicates poor localization accuracy of the corresponding point projections at the point matching step. It is also typical for false matches” (Agisoft 2018b).

There are two other types of errors that result in poor model accuracy, which should be mitigated during image alignment. Reconstruction uncertainty is described by the area enclosed by the lines drawn from an image point and the reprojection point of two overlapping images that contributes to noise in the point cloud (Figure 6). Projection accuracy causes poor keypoint positioning as a result of matching errors due to large keypoints. Points with high reconstruction uncertainty and low projection accuracy can be removed to improve the accuracy of the sparse point cloud and subsequent dense point cloud and mesh.

The remaining error in the model after removing points with high reprojection error, high reconstruction uncertainty, and low projection accuracy can accumulate and cause significant error. Models have a tendency of drifting from the ground truth along an axis. Traditional survey control points are used to reduce drift. Control points are placed in locations that are visible in the images and surveyed by traditional means. Control points are identified in the images and the model is provided with their 3D coordinates. The calculated location of the cameras can then be optimized considering the position of the control points. An additional function of the control points is to provide scale and orient the model. Check points are also included in the scene and surveyed but not used to refine the location of the cameras. These serve as a check on the obtained accuracy of the model. Check points are critical in assessing the actual accuracy of the model.
2.3.2 Model Segmentation

The computer resources required for SFM processing increases with the number of images in a project. Certain steps are more reliant on different computer components. The central processing unit (CPU) is the main component used for image alignment and dense point cloud generation. RAM is the main component for mesh generation. Increasing the number of images in a model increases processing time for CPU-dependent steps, whereas there is a limit on the number of images for RAM dependant steps. RAM is also used during CPU-dependent tasks, although the image limit is much higher. (Agisoft 2018b) recommends 48-144 GB of RAM for a model with 100 images.

2.3.3 Dense Point Cloud Generation

The quality of the dense point cloud generation is influenced by an image scaling factor, similar to that used during image alignment. The trade-off for increased quality is increased processing time. Processing the dense cloud at a reduced scale reduces the density of the point cloud, and to a lesser degree the accuracy of the
points. A high-quality image alignment mitigates some of the inaccuracy as a result of processing the dense point cloud at a lower scale.

### 2.3.4 Point Cloud Meshing and Image Overlay

The meshing process meshes the entire dense point cloud and then decimates it to the desired face count. This is the main factor for the significant RAM requirements for this step. Processing time is thus a function of the number of points in the dense point cloud. The face count of a mesh is chosen based on end user computing requirements. A higher face count increases the level of detail in the mesh and the resources required to visualize it.

Images are overlain on a mesh based on a texture map that positions the images in the correct location. The resolution of the overlain images is dependent on the size of the texture map and the number of texture maps used. The size of a texture map is given in pixel dimensions and multiple texture maps can be generated for a single mesh to increase visual resolution. The maximum size that can be generated and visualized is dependent on the capabilities of the graphics processing unit (GPU).

### 2.4 Accuracy

Accuracy is often the primary consideration when selecting technology for spatial documentation, yet the term is often used to describe several spatial characteristics of 3D models. Accuracy is commonly used to describe absolute accuracy, relative accuracy, and resolution of 3D models. Pix4D (2018) clearly defines absolute and relative accuracy of 3D models:

*Relative accuracy: ... the accuracy that is defined by comparing individual features on a ... reconstructed model ... with other features on the same model.*
Absolute accuracy: ... the accuracy that is defined by the difference between the location of features on a ... reconstructed model ... and their true position on the Earth.

Relative accuracy describes the closeness of a measurement between specific points within the model to a true value without consideration of the position of the model in real world coordinates. Absolute accuracy compares the position of a point in the model and the actual position of the same point in a real-world coordinate system.

The resolution or density of a model is commonly referred to as accuracy and describes the spacing of points within a model. A large point spacing may omit important details, whereas a closer point spacing will capture additional details, thus a more accurate model. For example, a 1 m point spacing may provide accurate relative or absolute accuracy but may be considered inaccurate as there may be significant spatial variations between the points that are not captured.

As discussed in Section 2.3.1, keypoint misalignment contributes to several types of errors. Camera optics play a large role in these errors. Distortions introduced in images due to low quality optics can increase keypoint misalignment, thus decreasing the accuracy of the resulting mode. Survey control points are used to correct drift in the models, although the inaccuracy of the survey control points must be considered when determining the accuracy of the photogrammetric model.

2.5 Summary

Inspecting hydroelectric tunnels has many challenges as outlined by Wang and Lee (2013). These challenges illustrate the effort required to complete an inspection. A successful inspection requires the coordination of multiple personnel from a variety of disciplines. The planning effort described by Ganse et al. (2016)
demonstrates the need for an efficient inspection to minimize the inspection costs as well as costs associated with plant downtime. The study by Shelton et al. (2016) highlights that proper upfront planning is critical to the success of an inspection, both from cost and safety perspectives. There is also value in documenting inspections in a standardized manner to allow for comparisons between subsequent inspections and to identify trends in deterioration.

The hydroelectric tunnel inspection methods identified in the literature are similar to those used by NB Power to document the Grand Falls intake tunnel. Inspecting hydroelectric tunnels is largely a manual task relying on visual observations, although more advanced inspection methods are beginning to be explored. Mohta et al. (2016) demonstrate the visual and spatial condition of penstocks can be documented autonomously with a UAV, although there are some significant limitations that need to be overcome to create a viable and consistent inspection method.

Data capture technology to document the visual and spatial condition of the Grand Falls intake tunnel in a 3D model was assessed. Candidates include mobile LiDAR, stationary LiDAR, and photogrammetry. Pejić (2013) notes that 3D data can be difficult to interpret and recommends converting 3D data into 2D drawings for interpretation. It could be argued that recent advances in computing power have the potential to eliminate the need to convert 3D models into 2D drawings for presentation. Software specifically designed for 3D visualization, such as that developed by Chmelina et al. (2012), is a powerful tool that facilitates data interpretation and identifying relationships between datasets. Incorporating 3D visualization tools may facilitate presentation of the models and permit greater
knowledge of the model than could otherwise be obtained from a 2D representation.

Structure from motion photogrammetry incorporates high resolution images and high accuracy spatial data. Maintaining detail in large scale models is a challenge. The hierarchical approach developed by Khaloo and Lattanzi (2016) integrates multiple imaging networks to maintain details in large scale models. Maintaining a high level of detail throughout an entire large-scale model, such as the Grand Falls intake tunnel, may be possible with a similar approach, where multiple high-resolution models are generated independently and then merged into a global model. This would provide inspectors with detailed information of the entire model, rather than specific areas recognized at the time to be of interest. Sub-millimeter resolution within a point cloud provides inspectors with impressive detail.

The accuracy of SFM models can vary significantly. The major factor to consider is the accuracy required for the project and selecting equipment and designing the data capture process appropriately to ensure the accuracy is met.

A critical factor in the success of an SFM model is the data acquisition technique. SFM requires overlap between subsequent images, which can be difficult to produce hand holding the camera in certain applications. This is especially true in canals, as noted in Charbonnier et al. (2013), where a specialized barge was constructed. The walls and ceiling of tunnels are difficult to reach and equipment to position the camera would facilitate data capture and ensure camera positioning requirements are met. A data acquisition system appropriate for the environment is essential for efficient SFM modelling.
UAVs are an efficient means of capturing images in difficult to reach areas and more importantly are able to capture images with the specific requirements for SFM post processing. Using SFM in a tunnel environment would benefit from some type of equipment that can position the camera appropriately, which could potentially be a UAV or other equipment designed specifically for the environment as was done with the barge in Charbonnier et al. (2013) to capture images of a canal.
3 Motivating Case

The traditional method used to inspect the Grand Falls Generating Station intake tunnel has several limitations that hinder rehabilitation planning. Hence, there is an opportunity to develop an improved inspection system to overcome these limitations and facilitate rehabilitation planning.

3.1 Limitations of the Traditional Inspection

The traditional inspection is consistent with the common inspection techniques found in the literature for hydroelectric tunnels (Section 2.1.1). The traditional inspection does provide an indication of the condition of the tunnel, although there are several areas that could be improved. Three main limitations are identified:

- difficulty visualizing deterioration and deterioration patterns throughout the tunnel,
- low accuracy in determining the location and size of defects, and
- the selectiveness and subsequent interpretation of an inspection.

The 2012 Grand Falls intake tunnel inspection contains three pages of defects, which is a total of 160 defects. Extensive data that describes a 3D object that is documented in tabular format is difficult to visualize and extract meaningful information. Trends and relationships can easily go unnoticed. The few photographs of defects that are provided are a useful reference, although they are dark and the orientation of the camera can be uncertain. The narrow field of view of the camera captures a close view of the defects but without showing the surrounding area, the photographs lack context and can be confusing.

Accuracy of the location and size of defects is anticipated to be quite low in the traditional inspection given it is conducted standing on the invert of the tunnel.
Defects on the ceiling of the tunnel would be upwards of 6 m away from the view of the inspector and the most common location of holes is at 1 and 11 o’clock upstream of radial construction joints (SNC-Lavalin Inc 2007). Low accuracy is likely a major source of error when comparing the changes in deterioration between subsequent inspections. Predicting future condition and what repairs and investment may be required will be difficult without a good sense of the deterioration trends.

The traditional inspection is inherently selective in nature. An inspector documents defects that they notice and types of deterioration that they feel important. What gets documented could also change between inspections depending on who conducts the inspection. An expert in concrete deterioration may be interested in characteristics that do not get documented in the inspection. This expert is also required to interpret the condition of the tunnel based on what was documented during the inspection. The condition assessment has a high level of subjectivity.

The limitations identified in the traditional inspection make managing the Grand Falls intake tunnel challenging. Management decisions are based on a very limited data set. The traditional inspection has limited ability to document the true condition of the intake tunnel and is not a good basis for predicting future condition. Management and rehabilitation is thus challenging. Maintenance activities are difficult to prioritize, schedule, and allocate appropriate resources. Repairs are difficult to design, and contractors are ill-informed and must adapt to actual conditions to remain on schedule. The end result is inefficient lifecycle spending.
3.2 Purpose of an Improved Inspection System

An improved inspection system was developed in consultation with NB Power personnel to overcome the limitations presented in Section 3.1. The overarching objective of the improved inspection system is to document the visual and spatial condition of the entire concrete-lined section of the tunnel and deliver it in the form of a 3D model. The inspection system must also meet project constraints.

Visual and spatial documentation are considered to be equally important because each provides unique information that describes the condition of the tunnel. The combination of visual and spatial data has a greater value than either in isolation. Integrating both in the same 3D model will facilitate visualization and combine the two data sets in an intuitive manner. The accuracy and resolution need to be suitable for capturing the size of defects observed in the tunnel and allow comparisons between subsequent inspections to identify trends and make predictions of future condition. Capturing the entire concrete-lined section of the tunnel will remove the selective nature of the traditional inspection method and provide a much more comprehensive understanding of the tunnel’s condition.

The most significant project constraint was the planned duration of the shutdown. The shutdown was scheduled for a two-week period at the end of August 2017. A few days of the shutdown were required for dewatering and watering back up. The inspection proceeded during the remainder of the shutdown without conflicting with other work being completed in the tunnel.

The harsh tunnel environment was verbally described to convey the conditions that personnel and equipment are subjected to. There is no light other than what is provided by light sources brought into the tunnel. It is also very wet with
sections where water sprays from cracks in the concrete liner similar to a garden hose. There is also a steady stream of water running down the invert of the tunnel. The temperature is cool, approximately 10-15 °C.

Getting equipment into the tunnel is also a significant constraint. Personnel enter the tunnel through the scroll case access hatch of unit number two, which is approximately 0.6 m in diameter. A larger rectangular access hatch, approximately 1 m square, is located downstream from the surge tank and is used to bring in equipment and materials.

Use cases identified for the proposed inspection system are summarized in Figure 7. Visualization and communication of the deterioration will allow assessments and predictions to be made, as well as plans to rehabilitate deterioration. The scope of this research project does not specifically encompass these use cases, rather it provides a 3D model that permits their application by others.

![Figure 7](potential_use_cases.png)

**Figure 7 – Potential use cases for the improved inspection system**

### 3.3 Selection of 3D Capture Technology

In summary, the improved inspection system needs to capture both visual and spatial data and have the ability to generate an accurate and high-resolution 3D model of the entire concrete-lined section of the tunnel in the expected environmental conditions. The inspection system also needs to be efficient so that
the entire concrete-lined section of the tunnel can be captured during the duration of the two-week shutdown.

Of the 3D technologies reviewed in Section 2.2, LiDAR, mobile LiDAR, and SFM photogrammetry were considered as potential candidates. Stationary LiDAR has high spatial accuracy and does not require light to capture spatial data. Some LiDAR units have built-in cameras to integrate visual data, although the resolution is not high enough to capture defects with sufficient detail. Mobile LiDAR has the advantage of being able to capture spatial data at a walking pace, although the accuracy is much lower than stationary LiDAR. Visual resolution is also much lower than stationary LiDAR. The main drawback to mobile LiDAR is the requirement for significant and frequent spatial variations, which are not present in the tunnel, in order for the system to generate a model. Photogrammetry has the potential for high spatial accuracy and high visual resolution. Capturing SFM data of a 3D object is complex and requires positioning the camera in potentially difficult to reach areas. It is typically not used in large indoor environments as a result.

The technology that best meets the objectives of the improved inspection system and has the ability to function within the project and environment constraints is SFM photogrammetry. A major challenge in capturing all of the photographs required to build an SFM model is positioning the camera efficiently and maintaining the required overlap between images and the desired distance from the surface. A data acquisition system will be required to facilitate positioning the camera throughout the tunnel.
4 Data Acquisition

Images are the foundation of an SFM model. The quality of the model is reflective of the quality of the images captured. Images that are well exposed, sharp, and have minimal distortion are critical, as is the positioning of the camera to document the object. The optimal position of the camera for SFM is perpendicular to the surface being captured. Maintaining a consistent height from the surface is also important as it affects the GSD and therefore the resolution of the model. An efficient method of capturing the interior of a cylindrical object, such as the tunnel, is by rotating the camera at some radius from the center of the cylinder as shown in Figure 8. Extracting geometry from overlapping images requires the position of the camera change between overlapping images to permit triangulation between common points to generate 3D geometry. (Rotating the camera at the center of the tunnel would not cause sufficient movement of the camera position to accurately extract 3D geometry.) This method captures images perpendicular to the surface of a specific section of the tunnel; the length of the section captured corresponds to the field of view of the camera. Subsequent sections are then captured with sufficient overlap of the previous sections.

4.1 Photogrammetric Parameters

Photogrammetric parameters are the main constraint on the details of positioning the camera. These parameters are largely influenced by the type of camera used. There are many digital photography formats available. The photogrammetric inspection system is designed based on a full frame digital SLR format.

Photogrammetric parameters of interest that influence camera positioning are the GSD, the field of view of the camera, and the overlap between images. These
parameters also dictate the number of images that will be required and therefore
directly influence the length of time required for data capture.

Figure 8 – Illustration of the required camera position and rotation

The primary consideration is the GSD as it has a large influence on the accuracy
and resolution of the resulting model. This term arises from aerial photography
where the GSD is defined as the distance between pixel centers measured on the
ground. The expected accuracy of SFM is one to three times the GSD, as
discussed in Section 2.2.2. Changing the GSD is achieved by changing the size of
the pixels on the camera sensor, the height of the camera above the surface, and
the field of view of the camera lens. Full frame digital SLR cameras have similar
pixel sizes between manufacturers, thus the main variable for changing the GSD
is the height and the field of view of the camera. Moving the camera further or closer to the surface increases or decreases the GSD, respectively. An important factor that must be considered is the increase in the number of images required as the camera is moved closer to the surface.

The field of view of a camera is affected by the focal length of a lens. A shorter focal length increases the field of view, which is desirable from the perspective of reducing the number of images required to capture the entire concrete-lined section of the tunnel. A lens with a wide field of view captures a larger area, thus fewer images are required. There are two factors that constrain how wide a field of view can be used for SFM photogrammetry with acceptable results. As the field of view increases, there is an increase in GSD because the pixels on the camera sensor represent a larger area. Increasing the GSD reduces the potential accuracy and resolution of the model. Distortion is also a consideration with short focal length lenses. There are two main types of lenses produced for full frame digital SLRs: rectilinear and fisheye. Straight lines viewed through a rectilinear lens appear straight, whereas straight lines viewed through a fish eye lens have significant distortion and no longer appear straight. As the focal length decreases, lenses become fisheye. Accurate SFM models require minimal distortion.

Front and side overlap are terms that are commonly used when capturing images with UAVs. UAVs capture images of an area in strips for an efficient flight. There is overlap between images within a strip, as well as overlap between adjacent strips. Front overlap refers to the overlap between an image and the next image within a strip and side overlap refers to the overlap between strips. To distinguish between the two types of overlap associated with data capture in
the tunnel, front and side overlap are referred to as primary and secondary overlap, respectively, herein.

The absolute minimum primary overlap required to extract 3D geometry is 50%. Capturing images with a target of only 50% primary overlap has significant risk. The 3D position of overlapping points would be determined by only two images. Larger primary overlap is recommended to introduce redundancy and also flexibility in post processing. A large primary overlap allows minor deviations in the planned position of the camera without losing the ability to extract geometry. Greater primary overlap also reduces the uncertainty of the 3D position of a point as it is triangulated between multiple images. In some cases, images may need to be discarded from processing due to poor quality or obstructions. A large primary overlap permits several sequential images to be removed without losing the ability to extract geometry. Secondary overlap requirements are lower than primary requirements, although maintaining a secondary overlap greater than the minimum is desirable. Recommended primary and secondary overlap are 80% and 60%, respectively (Agisoft 2018b, Pix4D 2018).

Time estimates to complete the inspection were established by dividing the inspection time into two components: the time to rotate the camera and scan a section of the tunnel and the time to advance the camera to the next station. Preliminary estimates of the number of images required to capture the entire concrete-lined section of the tunnel and the time required were in the order of 33,000 images and 21 days. This was reduced to approximately 4,500 images and four days through careful selection of the parameters discussed. An inspection requiring four days is acceptable and allows time should there be unforeseen
problems. The time estimates are contingent on the ability to position the camera as required.

The selected photogrammetric parameters are as follows:

- 5 m camera height
- 20 mm focal length rectilinear lens
- 1.6 mm GSD
- 80% primary and 60% secondary overlap

Given the selected photogrammetric parameters, the rotational axis is chosen as the primary overlap to minimize the number of longitudinal stations. The photogrammetry parameters require thirteen images throughout the rotation to provide an 80% primary overlap. The secondary overlap is the longitudinal length of the tunnel. A spacing of 2.4 m longitudinally provides a 60% secondary overlap.

4.2 Tunnel Inspection Assistant Design

Collecting high quality images throughout the 822 m within the shutdown period is a significant challenge. Positioning the photography equipment as illustrated in Figure 8 within the estimated time of four days requires some type of mechanical assistance. A tunnel inspection assistant (TIA) was designed and fabricated to facilitate data capture. Figure 9 illustrates a short section of the tunnel showing TIA with a six-foot person to demonstrate scale and the challenge of positioning the camera.

The main components of TIA include the frame (Figure 10), electronics and controls, and photography equipment. The frame provides support for the
photography equipment and the electronics rotate and trigger the photography equipment in a semi-autonomous manner.

4.2.1 TIA Frame

The frame design in Figure 10 is the result of several design iterations, which are chronicled in Appendix A, that simplified data capture and reduced weight. Earlier versions consisted of a rectangular horizontal frame with four wheels and additional bracing to support the vertical “A” frame. The three wheeled “A” frame design allows all wheels to remain in contact with the ground.

Figure 9 – Section of tunnel with TIA and six foot tall person
on rough terrain, providing stability for the photography equipment. The reduced weight facilitates moving TIA along the length of the tunnel, which is done by hand using the handle on the front wheel. The front wheel can turn to steer TIA and has a parking brake to ensure TIA does not move while capturing images. Without some form of restraint, TIA would tend to roll down the 1.5% slope.
The frame consists of a horizontal “A” frame, a vertical “A” frame and a boom, and can be disassembled into these primary components for easy transport. The majority of the frame is constructed from aluminum hollow structural sections.

The length of the horizontal “A” frame is such that the center of gravity remains in front of (i.e. toward the steering wheel) the vertical “A” frame so TIA does not overturn with the weight of the boom and photography equipment. The top of the vertical “A” frame is positioned at the center of the tunnel and connects to the boom with a steel shaft that rotates on two pillow bearings. The shaft is connected to a stepper motor, which is controlled by a microprocessor. The length of the boom is such that the rear wheels are not in the field of view of the camera. Adjustable mounting plates allow easy adjustments to the position of the photography equipment. The camera can be configured to capture images at a distance of 5 m as specified by the photogrammetric parameters. By rotating the camera (i.e. the field of view) 180 degrees, TIA can be configured to capture images at a distance of 3 m for increased resolution. The two configurations are dimensioned in Figure 9 in Section 4.2. A counter weight balances the rotation of the boom to reduce the load on the stepper motor. With the boom balanced, the only force the stepper motor has to overcome besides friction in the bearings is acceleration and deceleration. By disconnecting the braces, the vertical “A” frame can fold down to lower the boom so that photography equipment can be mounted from the ground.

Outriggers by each back wheel level and stabilize TIA while the boom rotates and captures images. Movement in the frame during image capture could cause motion blur in the images. Raising and lowering the outriggers is done by linear actuators. The outriggers manually extend laterally for additional stabilisation.
4.2.2 Electronics and Controls

Two main electronic systems were designed, programmed, and assembled by the author to facilitate operation of TIA. The imaging control system semi-autonomously captures images at each station along the length of the tunnel. The stabilisation system is manually controlled to level and stabilize TIA during image capture.

The imaging control system consists of a microcontroller, a push button control panel, a stepper motor, and two Wi-Fi modules. The microcontroller communicates with the stepper motor through a wired connection and the camera is triggered wirelessly. One Wi-Fi module is connected to the microcontroller and the other to the camera trigger. The rotation of the boom complicates the use of a direct wire connection between the microcontroller and the camera trigger.

The microcontroller is preprogrammed to perform specific actions with the stepper motor and camera trigger based on inputs from the control panel (Figure 11). The control panel has five push buttons associated with the microcontroller and is located on the long brace near the handle for easy access. Four of the buttons are in use and one button is reserved for future features. The buttons of the control panel are used for the following purposes:

- Start (SCAN)
- rotate clockwise (CW)
- rotate counter clockwise (CCW)
- power on/off (PWR)
The start button initiates a program to begin image capture. The program rotates the boom to the clock location of the first image and stops, waits two seconds for movement in the frame to stabilize, and then triggers the camera shutter and flash. This process is repeated until 13 images at the station are captured. The stepper motor accelerates and decelerates to mitigate unwanted movement in the frame. The rotate CW/CCW buttons allow manual rotation of the boom should it need to be repositioned prior to capturing images or for access to the photography equipment. Stepper motors draw full current whether they are rotating or not. The power on/off button allows power to the stepper motor to
be turned off to conserve batteries when image capture is not occurring. The microcontrollers and Wi-Fi modules are individually powered by 5V power packs, and the stepper motor is powered with a 12V, 32Ah utility vehicle battery. A 32 Ah battery is sufficient to power the stepper motor for a day provided power is turned off when rotation is not occurring. Recharging overnight is required.

The stabilization system consists of linear actuators that raise and lower legs to level and stabilize TIA. Each linear actuator is controlled with a simple double pole, double throw switch located on the control panel. The system is powered by a separate 12V, 32 Ah utility vehicle battery and is sufficient for raising and lowering all three legs at each station for one day. Recharging overnight is required. The size of the batteries for both the imaging and stabilization systems are minimized to reduce the effort required to transport them in and out of the tunnel.

4.2.3 Lighting Equipment

Lighting is required for proper exposure using sensor sensitivity, as described by the International Organization for Standardization (ISO), aperture, and shutter settings suitable for photogrammetry. The amount of light required is a function of sensor sensitivity (ISO), shutter speed, and aperture. For photogrammetric purposes, a low ISO, small aperture, and high shutter speed is desirable. ISO is a measure of the sensor's sensitivity to light. Increasing ISO reduces lighting requirements, although it also introduces undesirable noise, which can reduce the accuracy of feature point matching between overlapping images. Shutter speed is the length of time the shutter remains open during an exposure. Longer shutter speeds reduce lighting requirements but increase the risk of motion blur if the camera is moved during an exposure. Aperture is a measure of the size of the
opening to admit light through the lens and is noted as f-stops. Larger apertures reduce lighting requirements, but result in a shallow depth of field, ultimately risking images that are not in focus.

Lighting requirements are further increased by the use of cross polarization, a technique used to reduce glare, which is anticipated in the tunnel due to smooth, wet surfaces. Light reflects off surfaces as either a specular of diffuse reflection. Specular reflection occurs when the angle of incidence of a ray of light is equal to the angle of reflection. Diffuse reflection occurs when a ray of light is reflected in many different directions.

Light vibrates in many planes. Linearly polarized light is restricted to vibration in one plane. Linearly polarized light reflected as a specular reflection maintains its linear polarization, whereas diffuse reflections do not. Polarization filters are used on the light source to polarize the light. A polarization filter is also used on the camera lens. Specular reflections are reduced by orienting the polarization filter on the camera so that the linearly polarized light is not able to pass through to the lens. The addition of polarization filters increases lighting requirements approximately three times.

Flash lighting is used rather than continuous lighting due to the greater light output and lower power requirements. The flashes are wirelessly triggered by the camera during image capture. External power packs are used to reduce delays caused by slow recycling, thermal shut down, and battery recharging. Four flashes were used and provide a less than ideal exposure of ISO 1600, aperture 3.2, and shutter 1/160s, with the polarization filters. Additional flashes were not available to decrease ISO and aperture. A trade off was made between ISO and aperture.
to balance noise and image sharpness. Wide apertures near the limit of a lens produce less sharp images. A lower ISO could be used to reduce noise at the expense of image sharpness. An aperture of 3.2 was found to produce an acceptable sharpness and depth of field. With the lens focused at 5 m, the depth of field extends from approximately 4 m to 6 m. The shutter does not affect the exposure of flash photography as the duration of the flash is significantly shorter than the maximum speed (shortest exposure duration) at which the shutter can synchronize with the flash. The maximum shutter speed is limited to 1/160 of a second on the camera used.

4.3 Inspecting the Grand Falls Intake Tunnel

The generating station was taken offline over the weekend of August 19th, 2017, for an anticipated tunnel entry on Monday the 21st. Dewatering complications delayed entry and mobilizing TIA until late the following day. TIA was disassembled and lowered through a vent in the horizontal intake shaft and down the vertical riser section as the access hatch near the surge tank was not large enough. Data acquisition began on Wednesday, August 23rd and continued until Monday August 28th, at which time the entire concrete-lined section of the tunnel had been scanned at a camera height of 5 m, as well as a 30 m section at a camera height of 3 m. Additional scanning was completed on Wednesday August 30th to capture an 8 m section where repairs in the concrete liner were completed to allow before and after comparisons with the model. The tunnel was watered back up ahead of schedule late Wednesday August 30th.

Survey markers were placed in the tunnel prior to scanning to use as control and check points in the model. Control points are used to correct drift that accumulates in photogrammetric models due to the error in keypoint matching.
Check points are used to assess the accuracy of the model. The markers consisted of a nail with a washer, and a piece of wire to secure the nail in a drilled hole. The size of the marker was sufficient to easily identify them in the images. Control points were placed every 33 m along the length of the tunnel on alternating sides. This distance corresponds to the placement of control points for the traditional inspection method. Check points were placed opposite from each control point. Placing control points on alternating sides ensures the model is fixed in space. Control points along one side of the model would not provide a strong anchor and could allow the model to rotate about the longitudinal axis of the tunnel. Figure 12 is an image of TIA in the Grand Falls intake tunnel capturing images in the 3 m configuration. The umbrella observed in the image was used to protect the photography equipment from water dripping or spraying from cracks in the concrete liner.

The scanning process involved positioning TIA at a station, capturing that section of the tunnel, and advancing 2.4 m to next station. Positioning TIA at a station requires checking for level and center alignment. Outriggers were used to level TIA if a wheel dropped into a hole, although they were rarely required. Center alignment could be adjusted by manually shifting TIA laterally, although center alignment was easily maintained with careful alignment during advancement to the next station. Once positioned at a station, the boom was manually adjusted (rotated) into the start position, which pointed the camera straight down. A consistent start position facilitated quality control. With the boom in the start position, image capture was initiated. During image capture, images were automatically, wirelessly transferred to an iPad for review (Figure 13). After completing the image capture at a station, TIA was advanced to the next station. Measuring the advancement and positioning of the next station was done with a
Image of TIA capturing images in the 3 m configuration
large washer attached to a string of the appropriate length. The string was pulled taut and the washer placed on the ground. TIA was advanced until the front wheel was abreast of the washer.

Two main issues were experienced and extended the estimated capture time from four days to seven days:

- one or more of the flashes not firing resulting in under exposure, and
- the camera not triggering on one or more images at a station.

Both of these issues required recapturing an entire station when they occurred. The iPad was essential for quality control and ensured that these issues were corrected prior to advancing to the next station. The review screen on the iPad was set up so that images from one station fit on a single row (Figure 13). This created consistency through the columns of images and issues with exposure were easily identified by comparing with previous images in the same column. Missing images were also easy to identify as the rows would no longer align vertically.

The cause of the camera not firing was either from dead camera batteries or a full memory card. Flashes not firing was more frequent than the camera not triggering and was either from overheating or dead batteries. Overheating was caused by capturing images too quickly and was resolved by delaying the advance to the next station, which allowed sufficient time for the flashes to cool.

4.4 Summary

Over 5,000 images were captured in the 5 m configuration along the 822 m main concrete-lined section. A high-resolution test with the camera in the 3 m configuration was completed in a 30 m section. This length was chosen so that
two control points could be included in the model to facilitate referencing for comparison with the model captured at 5 m. TIA facilitated positioning the camera and allowed the entire concrete-lined section of the tunnel to be scanned within the shutdown period. A total of seven days was required to scan the 822 m section. With minor improvements to TIA based on lessons learned with flashes overheating and the camera not firing, it is anticipated that the inspection time could be reduced to four days with the same equipment. Additional time reductions could be realized by redesigning TIA or using multiple TIAs.

Figure 13 – iPad used for quality control of captured images
5 Data Modelling and Delivery

Data modelling and delivery are critical steps in the SFM workflow. Data modelling refers to the processing required to generate 3D models from the images. Delivery is the method used to visualize and interact with the models. Commercial software has facilitated SFM processing, although generating models can appear to be a black box process. Inexperienced users can easily point software at the captured images and generate a model without any indication of its quality. Interacting with the models is the last phase of work and is typically not performed by those generating the models. This disconnect can constrain the thought that goes into how the end user will interact with the model.

The deliverable of the Grand Falls modelling process includes dense point clouds and meshes with image overlays for three specific data sets:

- The 822 m concrete-lined section of the tunnel captured at 5 m
- The 8 m repair section of the tunnel captured at 5 m
- The 30 m high-resolution test section captured at 3 m

Dense point clouds as well as meshes with an image overlay are necessary to satisfy the requirements of delivering the inspection with high spatial accuracy and high visual resolution. Dense point clouds are suitable for delivering high spatial accuracy and meshes for high visual resolution. The choice of which type of model is based on computer requirements. A point cloud can be generated at a density that sufficiently captures the details of an object, although a density that is comparable to the resolution of the images requires significant computer processing and storage requirements. Displaying a high-resolution image on a 3D model requires a solid surface. Meshing a point cloud creates faces that connect the points of a point cloud and thus contains much more data. The solid surface
of the mesh allows images to be overlain, although the addition of faces to connect the points dramatically increases computing requirements. The faces of a mesh are reduced to decrease demands, but this is at the cost of reduced spatial accuracy.

5.1 Data Modelling
Data modelling consists of several steps, which are discussed in Section 2.3. The following sections detail the inputs and outputs of each step. Modelling was completed with Agisoft Photoscan (Agisoft 2018a), although the inputs are relevant and similar to other software packages.

5.1.1 Image Alignment
Image alignment is arguably the most critical step in producing an accurate model as it forms the basis of subsequent processing. The tunnel was aligned at full image resolution and a reprojection error of 0.341 pixels was achieved after removing poor quality points. Control points were placed in the tunnel as described in Section 4.3. The RMS error of the check points before and after optimizing cameras with survey control was 4 m and 5 mm, respectively.

5.1.2 Model Segmentation
The Grand Falls tunnel has over 5,000 images and would require approximately 2,400-7,200 GB of RAM to process as a single model. A computer with this amount of RAM is not practical with current computer technology. Dividing the model into smaller sections after image alignment can reduce computation requirements by reducing the number of images in a model. Processing the tunnel in smaller sections also has the advantage of preserving fine details. As discussed in Section 2.2.2, fine details are lost in large scale models. Model segmentation is
best done after image alignment. Aligning the images in a single model results in a more accurate model as the alignment considers all images and incorporates survey control points, which might not be included in each segment.

The tunnel sparse point cloud was divided into 200 segments to process the dense point cloud and mesh with image overlay. One segment consists of approximately a 4 m portion of the tunnel.

5.1.3 Dense Point Cloud Generation

A dense point cloud of each segment of the tunnel was generated in sequence with images at a high resolution. Time limitations were the main reason for the scale chosen. Automated processing at this resolution required a total of approximately 2 weeks and resulted in approximately 4 million points per point cloud.

5.1.4 Point Cloud Meshing and Image Overlay

Each segment of the tunnel was meshed with a target face count of 60,000 faces. This face count was chosen primarily based on model delivery requirements, discussed in Section 5.2. Automated processing required approximately 2 additional weeks to complete. A single texture with a resolution of 8,192 by 8,192 pixels was generated for each segment based on GPU capabilities and delivery requirements (Section 5.2).

5.2 Model Delivery

The result of data modelling is as follows:

- 200 segments of the concrete-lined section of the tunnel captured at 5 m
- 5 segments of the repair section captured at 5 m
• 8 segments of the high-resolution section captured at 3 m

Each segment consists of a dense point cloud and a mesh with an image overlay. The dense point cloud and mesh segments can be visualized independently or merged into any number of models. The size of the models makes merging them into a single model not practical.

There are several methods to visualize and interact with the models. Standard CAD software or 3D modelling software, such as that used to generate the models, can be used, although these environments are not designed for inspection purposes. The tool set is specific to design and model manipulation, rather than inspecting infrastructure. A custom interface was developed to deliver the tunnel model with a tool set dedicated to inspection.

5.2.1 Interface Design

The 3D game engine Unity (Unity Technologies 2017) is the foundation of the custom interface developed to deliver the models. Game engines are well suited to visualizing 3D models and allowing intuitive navigation and interface customization. Navigation can be done with a variety of input devices. Currently supported devices in the interface include a keyboard and mouse, and a joystick game pad. The design of the interface includes inspection-specific tools, and operational features that allow the interface to visualize large models on a standard laptop computer. The main features of the interface include:

• Visualization of large models
• Overlaid contextual information
• Quick navigation
- Distance measurement
- 3D annotation and bookmarking
- Model comparison
- Expandable tool set

A view of the main interface window is presented in Figure 14 to highlight the end user features. The interface can be delivered as a standalone desktop file and has the potential to be delivered as a web-based application.

![Figure 14 – Main model visualization window of custom interface](image)

Interacting with the tunnel as a single model is challenging given its size. Each of the 200 segments contains approximately 4 million points in the dense point cloud and 60,000 faces in the mesh. Each mesh also has high resolution image overlays. Loading all of these models is not practical, nor possible on a standard laptop computer. It is important that the interface work on an average laptop computer so that the models can be easily accessed by interdisciplinary teams.
The interface is designed to load and unload individual segments as required at a resolution dictated by the distance of the view point to the segment. The two segments closest to the viewpoint are loaded in high resolution, as well as two on either side of the view point, for a total of six high resolution segments. Five low resolution segments are loaded on each side of the high-resolution segments to give the perspective of being in a large model for a total of ten low resolution segments, or a grand total of 16 segments. The lower resolution is not perceived as those segments are far enough away that fine details are not seen in high resolution segments. As the user navigates through the tunnel the interface seamlessly loads and unloads segments as the view point moves along the length of the tunnel.

The interface can be opened as a windowed application or be displayed full screen. As shown in Figure 14, a console is overlain at the top of the interface that can be turned on and off to increase the viewing area. The console consists of a plan view and section view to visualize the user’s current location in the tunnel, as well as numerical elevation, station, and measured distance information. The plan view also identifies which segments are loaded and not loaded by highlighting and dimming them, respectively. Clicking a location on the plan view allows the user to quickly navigate to a desired location.

A measurement mode can be enabled that allows the user to measure the distance between two points by clicking on the interface. Once a measurement is completed, additional measurements can be made by selecting new points.

Perceiving the depth of holes in the model is challenging due to the lack of shadows in the high-resolution image overlay. The image overlay can be disabled to view
a wireframe or shaded view of the mesh. The wireframe is well suited for visualizing the resolution of the mesh and performing measurements since the user can select vertices rather than faces, which are more accurate (Figure 15). The shaded mesh enhances depth perception. When either the wireframe or shaded mesh are enabled the user can exit the tunnel to view it from the outside, which also provides an enhanced perspective for depth.

![Image](image.png)

**Figure 15 – Model with wireframe on left and image texture on right**

Point of interest (POI) is a planned feature beyond the scope of this research to allow a user to document an inspection within the interface and share it with other users. Figure 16 is an example of the point of interest functionality. The information stored is similar to that of the traditional inspection. Voice recordings can also be created and stored with the text information.

Two models can be visualized and navigated simultaneously in the interface to facilitate comparisons over time. The user selects which models to view and they
are loaded side by side. The two models are loaded with synchronized view points and the navigation between them is also synchronized (Figure 17).

<table>
<thead>
<tr>
<th>POI</th>
<th>Station</th>
<th>Clock location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ▲</td>
<td>Go</td>
<td>0+010</td>
</tr>
<tr>
<td></td>
<td>4:00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Notes</td>
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</tr>
<tr>
<td></td>
<td>Hole extending to bedrock, need anchors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anchors designed</td>
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<tr>
<td></td>
<td>+ add note</td>
<td></td>
</tr>
<tr>
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<td>0+300</td>
</tr>
<tr>
<td></td>
<td>1:00</td>
<td></td>
</tr>
<tr>
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<td>Go</td>
<td>0+400</td>
</tr>
<tr>
<td></td>
<td>2:00</td>
<td></td>
</tr>
<tr>
<td>4 ▼</td>
<td>Go</td>
<td>0+500</td>
</tr>
<tr>
<td></td>
<td>3:00</td>
<td></td>
</tr>
<tr>
<td>5 ▲</td>
<td>Go</td>
<td>0+600</td>
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<tr>
<td></td>
<td>4:00</td>
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<tr>
<td>6 ▼</td>
<td>Go</td>
<td>0+700</td>
</tr>
<tr>
<td></td>
<td>5:00</td>
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<tr>
<td>7 ▼</td>
<td>Go</td>
<td>0+800</td>
</tr>
<tr>
<td></td>
<td>6:00</td>
<td></td>
</tr>
</tbody>
</table>

**Date**  
2018-01-01  
2018-02-01

**User**  
John  
Mike

**Notes**  
Hole extending to bedrock, need anchors  
Anchors designed  
Large patch, appears to be failing  
Repair not critical

+ add note

**Figure 16 – Planned point of interest feature**

**Figure 17 – Comparison mode to visualize two models simultaneously**
5.2.2 Summary

The custom interface allows intuitive interaction with large models on standard laptop computers. The motivation for developing a custom interface was the ability to deliver the model with an inspection-specific tool set. The current tool set is a starting point, and additional features are anticipated as the model is explored and used to support rehabilitation planning.

The interface was developed in collaboration with the Faculty of Computer Science at the University of New Brunswick (UNB). Weichang Du supervised Jesse Reid, who implemented the design and tool set requirements that the author specified.
6 Traditional and Photogrammetric Inspection Comparison

The results of a traditional inspection are difficult to visualize, inaccurate, and selective. Typically, these results also require interpretation by someone other than the person who performed the inspection. The 3D model accurately documents the visual and spatial condition of the entire concrete-lined section of the tunnel in an intuitive manner. Visual resolution is on the order of 2 mm and spatial accuracy is on the order of 5 mm. The 3D model also allows detailed assessments from an office environment by various personnel. Figure 18 is a view of the entire point cloud of the Grand Falls intake tunnel and Figure 19 is a detailed example of concrete lining deterioration in the point cloud.

Figure 18 – Point cloud of the concrete-lined section of the Grand Falls intake tunnel

Initial feedback from NB Power has been positive and supports the use cases identified in Section 3.2. “The 3D visual and spatial model ... will provide valuable information for future engineering assessments, job planning, contracting, repairs,
scheduling, and the location of future development of hydro in Grand Falls” (Hanscom 2017b).

![Figure 19 – Detailed view of deterioration in the Grand Falls point cloud](image)

From an asset management perspective, the photogrammetric inspection system substantially accomplishes the role of two of the four steps in the general framework (Figure 5). The photogrammetric inspection system accomplishes the data acquisition component and part of the analysis and processing component. Additional analysis and processing to further extract information and to develop deterioration models will be much easier now that this 3D model has been created as noted in Section 3.2.

The data collected are the foundation of the asset management framework and decisions are made based on the data collected. The improvements of the photogrammetric inspection system over the traditional inspection thus enable better informed decisions, as well as a record of the basis for these decisions, and therefore instill confidence in their implementation.
An investigation was completed to assess deterioration of the concrete lining between the photogrammetric model and the traditional inspection. A 30 m section of the model was compared to the same 30 m section in the 2012 inspection report to assess the differences between the inspections. Deterioration documented at specific stations varied considerably between inspections and it was not possible to identify all of the records of the traditional inspection in the model with confidence. The following points are conclusions from the investigation.

- The variation in documented deterioration between inspections highlights the ability of the model to document the actual conditions of the tunnel. It is possible that further deterioration has occurred between the 2012 inspection and the model. This could account for some of the differences, although additional deterioration was noted in the traditional inspection that is not observed in the model.
- The clock location, station, and size of deterioration in the traditional inspection is not accurately documented and contributes to the inability to identify deterioration between inspections.
- The model documents much smaller cracks than the traditional inspection, which could potentially lead to larger holes and even dislodgment of large sections of the concrete liner in the future. The smaller cracks identified in the model could be used to predict future deterioration as well as the timing of repairs. The traditional inspection mainly documents larger holes and cracks that already need repair.
- The inaccuracy of the traditional inspection, as well as the ability of the model to document smaller cracks highlights that decisions regarding the
management of the tunnel are being made without an accurate understanding of its actual and predicted condition.

- Defects on the tunnel invert are not easily identified in the model due to the stream of water. The model also lacks the tactile experience gained during an on-site inspection.

A comparison of the traditional and photogrammetric inspections is summarized in Table 1. Each parameter was assessed, and the inspections ranked as being either better (+) or worse (−) than each other. A Ø is used to denote parameters where there is no considerable difference between inspections. The table is split into two categories: comparable parameters and new benefits. The traditional inspection was never meant to meet several of the identified parameters, thus it would be unfair to include all parameters in a single comparison category.

- The speed of inspection considers preparation, on site time, and post processing to deliver the report or 3D model in the custom interface. These inspection components are also considered in the cost comparison.

- The cost of the traditional inspection is approximately $10,000. The cost of the photogrammetric inspection being performed by a consultant is estimated to be $40,000.

- Accuracy refers to both the size and location of deterioration.

- The ability to assess and predict condition, as well as plan rehabilitation are an assessment of the usefulness of the inspection in supporting those activities.

- The analysis required after the inspection is an assessment of the effort required after delivering the final report or 3D model to assess the condition of the tunnel. The condition of the tunnel, whether accurate or not, could
be well known immediately after completing the traditional inspection and compiling the report and database. The accuracy of the condition determined by the traditional inspection is largely dependent on the experience and knowledge of the inspector and could vary. Condition is not well known with the photogrammetric model until after the 3D model is delivered and an inspection completed with the model.

- Comprehensiveness describes the completeness and level of detail of the inspection. The photogrammetric model documents the entire concrete-lined section of the tunnel, essentially capturing all deterioration, whereas minor deterioration is omitted from the traditional inspection. The photogrammetric model documents deterioration with a 2 mm visual resolution, capturing small cracks as well as large holes (Figure 20). The traditional inspection lacks these smaller details. As a result, better predictions of deterioration, as well as the timing of repairs, can be made with the photogrammetric model.

- Alternative uses refers to the ability to facilitate activities other than assessing and predicting condition, and planning rehabilitation, such as safety, training, and planning related engineering works (e.g. additional hydro projects in Grand Falls).

- The likelihood of experiencing benefits related to improved asset management includes reduced lifecycle spending, reduced risk of failure, and extended service life.

There are strengths and weaknesses to both inspection methods. The main consideration for selecting an inspection method is the time frame in which the deliverable is required. Should timing not be an issue, the photogrammetric
inspection system delivers a superior deliverable and the increase in cost is justified by the improvements.

Table 1 – Comparison of traditional and photogrammetric inspections

<table>
<thead>
<tr>
<th>Comparable Parameters</th>
<th>Traditional*</th>
<th>Photogrammetric*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Cost</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Accuracy</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Ability to assess and predict condition</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Ability to plan rehabilitation</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Effort required for data analysis after receiving deliverable</td>
<td>+</td>
<td>–</td>
</tr>
</tbody>
</table>

**New Benefits**

<table>
<thead>
<tr>
<th></th>
<th>Traditional*</th>
<th>Photogrammetric*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comprehensiveness</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Alternative uses</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Likelihood of experiencing benefits of improved asset management</td>
<td>–</td>
<td>+</td>
</tr>
</tbody>
</table>

* A “+” or “−” indicates this inspection is better or worse compared to the other, respectively.

Figure 20 – Example of the comprehensiveness of the photogrammetric model
7 Extension of the Photogrammetric Inspection System

The results of the Grand Falls models generated interest from other groups at NB Power who wanted to apply the photogrammetric inspection system to infrastructure at the Mactaquac Generating Station (herein referred to as Mactaquac). Mactaquac has six Kaplan turbines and a total capacity of 670 MW (Wikipedia Contributors 2017b). Each year two units are taken offline sequentially beginning in early summer through to early winter for inspection, maintenance, and repairs (Morales 2017). The planned shutdown of Unit #5 in early October 2017 presented an opportunity to assess the potential of the photogrammetric inspection system in a different environment.

7.1 Motivation

Mactaquac is affected by alkali aggregate reaction (AAR), which is causing the concrete of the entire dam to expand. The concrete cracks as it expands and displaces equipment throughout the facility. Significant repair and maintenance is completed on an ongoing basis to keep the facility operational. Detailed measurements are required to assess the condition of the facility and to reposition equipment. The use cases of the 3D models identified for Grand Falls in Section 3.2 are also applicable to Mactaquac. Two locations were identified to trial the technology to assist with AAR assessments: the turbine discharge ring and the draft tube (Figure 21).

7.1.1 Discharge Ring

The discharge ring is a stainless steel liner anchored in concrete that houses the turbine blades, which rotate on the vertical axis. The diameter of the discharge ring is 6 m. There are six blades approximately 2 m wide and 5 m long (radially) and angled at approximately 30 degrees to horizontal. When viewed from a plan
view perspective there is a slight overlap between the blades around the circumference of the discharge ring. A false floor is installed approximately 1 m below the bottom of the blades so that work can be completed on the discharge ring and blades. Figure 22 is a detailed elevation of the discharge ring. The area of interest is the discharge ring wall from the false floor up to the elevation indicated by point 13.

![Figure 21](image)

Figure 21 – Section of the Mactaquac Generating Station through Unit #5 (New Brunswick Power Corporation 1995)

A key parameter of the discharge ring that is affected by AAR is the gap between the blades and the stainless steel liner. The gap has strict tolerances; on the order of a few millimeters. If too big, the unit does not operate efficiently; if too small, there is potential for the blades to strike the discharge ring causing significant damage. This gap is shrinking as a result of the concrete expansion. There are two methods of managing a reduced gap. If the expansion is isolated to a specific area and there is sufficient clearance on the opposite side, the turbine can be
recentered to meet tolerances. If recentering is not feasible, the stainless steel liner can be machined to remove material in the required areas.

Figure 22 – Elevation of the Mactaquac Unit #5 discharge ring (New Brunswick Power Corporation 2001)

The gap has traditionally been measured with dial gauges. Measurements are obtained at 24 specific locations around the discharge ring at a single elevation. Interpolation is required between measurements. Finer dial gauge measurements are obtained in a 15 cm x 15 cm grid when required over the height of the turbine blade. This provides measurements throughout the height of the discharge ring, although interpolation is required between points. Assessing a tolerance of a few millimeters is challenging when the measurements are interpolated over 15 cm on a curved surface. The measurements are analyzed using spreadsheets and are difficult to visualize. Significant data interpretation is required to assess the tolerance and remediation options (Morales 2017).
Cavitation is also occurring on the stainless steel liner and blades (Figure 23). There is interest in assessing and documenting the loss of material visually as well as spatially if sufficient accuracy can be obtained. There is currently no method of documenting cavitation and repairs are assessed and made on an impromptu basis during each inspection. The accuracy required in order to measure blade gap as well as cavitation is on the order of 0.25 mm.

A 3D model would assist the inspection by accurately documenting the visual and spatial condition of the discharge ring in an intuitive format that can be analyzed in depth from an office environment. Ideally, measurements could be made anywhere within the model with ease, allowing a more thorough assessment of...
remediation options. Generating accurate 3D models is repeatable and comparing changes between models may be automated. This would facilitate assessments between rather than during shutdowns. A 3D model would also allow additional experts to interpret the actual condition of the discharge ring.

7.1.2 Draft Tube Bay Walls

The draft tube consists of a vertical and a horizontal section. The vertical section is circular (in plan view) and extends downward from the discharge ring and transitions into the horizontal section. The horizontal section becomes somewhat rectangular after it slopes upwards at approximately 20% and divides into three somewhat rectangular (in cross section) bays (Figure 24). The height of the horizontal section at the turbine end of each bay is approximately 2 m and increases to approximately 6 m at the tailrace end. Concrete expansion in the draft tube is causing significant cracking in the bay walls. The cracks are monitored for structural and operational purposes.

The traditional method of monitoring the cracks involves erecting scaffolding in the draft tube bays and tracing the cracks with crayons so they show up well in subsequent images. Tracing the cracks is subjective as the start and end points of the cracks are not clearly defined. Images are taken of the traced cracks and then stitched together as a panorama (Figure 25). Erecting the scaffolding and tracing the cracks is very labour intensive. The resulting panoramas have no scale; thus, the length of cracks cannot be determined accurately. There is also significant distortion in the stitched panoramas, as can be seen in the right most stitched image in the panorama displayed in Figure 25. The joint between the bay wall and the stop logs appears to be sloped at an angle of approximately 30 degrees from vertical, whereas in fact it is vertical, as shown in the original image.
in Figure 26. Assessing the progression of cracks is done by comparing panoramas over time. Accurately quantifying the progression of cracks is difficult given the subjectivity, lack of scale, and distortion in the panoramas.

A 3D model of the draft tube bay walls maintains the visual documentation of the traditional inspection and would also allow accurate measurements over the entire wall. With accurate scale, a detailed assessment of crack progression could
be performed in CAD by tracing the cracks from subsequent inspections. Finite element modelling is being done to predict the condition of the draft tube over time. The inspection models could be compared with finite element models to assess their accuracy and help calibration.

Figure 25 – Historical panorama of Mactaquac draft tube cracks

Figure 26 – Image of the cracks in the Mactaquac Unit #5 draft tube wall
7.2 Data Acquisition, Modelling, and Delivery

The process of data acquisition, modelling, and delivery for Mactaquac are similar to that developed for Grand Falls (Chapter 4 and 5). This section summarizes data acquisition, modelling, and delivery completed for Mactaquac and highlights differences from Grand Falls.

TIA was designed specifically for the dimensions and configuration of the Grand Falls tunnel and is not suitable for use in the discharge ring or draft tube. The discharge ring has a vertical configuration and has turbine blades throughout. The draft tube is rectangular and changes section height. There was insufficient time to design and fabricate a new data acquisition system to work in the discharge ring and draft tube, thus the camera was positioned manually. The reduced efficiency as a result of manual placement was acceptable for the trial and not significant given the small areas in comparison to the Grand Falls tunnel.

The camera was positioned manually with a tripod and custom head on which the photography equipment was mounted. The camera and lens used for Mactaquac are the same as that used for Grand Falls, therefore the photogrammetry parameters for the discharge ring and draft tube are largely the same as Grand Falls. The camera height was modified to suit the desired accuracy for each location.

7.2.1 Discharge Ring

Data capture in the discharge ring occurred over a period of four weeks and required 52 hours of effort. Twelve survey control points and four check points were placed prior to capturing images. Capturing images in the discharge ring is complex due to the 1 m camera height and position of the turbine blades. The height was chosen to achieve an accuracy sufficient for gap measurement and to
capture the fine details of cavitation. The GSD with the camera at 1 m is 0.33 mm. The expected accuracy is one to three times the GSD, as described in Section 2.2.2, which is 0.33 mm to 0.98 mm. The turbine blades reduced the working space and the slope of the blades made it challenging to manoeuvre. Figure 27 illustrates the complex data capture process. The blue boxes indicate the position and orientation of the camera.

Figure 27 – Camera positioning in the Mactaquac Unit #5 discharge ring

Images were captured in three phases. The area below the turbine blades was captured with the camera on the false floor. Circular strips were captured increasing in elevation until the camera reached the height of the bottom of the turbine blades. Images were captured from the false floor in strips increasing in elevation until the camera could be placed on top of the turbine blade. Images
were captured from the turbine blade in spiraling strips, increasing in elevation until the camera reached the height of the previous blade. After the area between all of the turbine blades had been captured, the blades were rotated by one half of a blade spacing. The process to capture the area between the blades was repeated to capture the area that was previously not visible. Lateral camera stations were manually measured and marked on the floor and turbine blades. The alignment of the camera to the discharge ring surface had to be manually checked for each image to ensure that the camera was perpendicular to the surface. Alignment was difficult to judge without measuring due to the curvature of the discharge ring. Measuring alignment for each image required significant effort.

Over 500 images were captured in the discharge ring. The greatest challenges were manoeuvring the camera on the turbine blades and measuring the camera alignment for each image. The tripod had to be held constantly to avoid overturning. Measuring the camera alignment for each image significantly reduced productivity. The initial technical challenges encountered at Grand Falls with the camera and flashes were not an issue.

The final deliverable is a point cloud rather than a mesh to preserve the highest possible level of detail and accuracy. The point cloud is extremely dense, containing 1.4 billion points. Modelling was completed at the highest quality in an attempt to achieve the desired accuracy. A reprojection error of 0.195 pixels was achieved. Global accuracy of the model is currently being assessed by NB Power personnel against dial gauge readings.
7.2.2 Draft Tube

Data acquisition in the draft tube required 30 hours of effort. Images of each wall were captured independently. The ceiling and floor were not captured due to time constraints. Eighteen control points were placed on the six walls, three on each. Given that each wall was scanned independently there are insufficient points to be used as check points. The three survey points on each wall are required to fix the position of the wall in 3D space.

Capturing the images in the draft tube was straightforward. A camera height of 3 m from the wall surface was chosen to satisfy accuracy and resolution requirements. The GSD at 3 m is 1 mm, and the expected accuracy is 1 mm – 3 mm, which is one to three times the GSD as discussed in Section 2.2.2. Images of each wall were captured in a series of strips, increasing in elevation by extending the tripod height. The camera stations were manually measured and marked on the floor to facilitate positioning. The alignment was not measured for each image because it could be judged well by eye.

Approximately 45 images of each wall were captured. The main challenge encountered in the draft tube was positioning the camera with the tripod extended 6 m high. At this height the tripod has a tendency to sway and could easily overturn. To avoid blurred images, movement in the tripod was allowed to dissipate before images were captured. The final deliverable for the draft tube are point clouds and meshes with image overlays for each wall. Control points on one of the walls could not be found in the images, thus it could not be oriented or scaled. Urethane injection was completed in the draft tube to seal the cracks between the time when control points were placed and the images were captured. It is suspected that urethane covered the control points. Modelling was completed
at the same quality as that done for Grand Falls and suited the uses of the models. The maximum deviation of the model from the survey control points is 3 mm.

### 7.3 Summary

The photogrammetric process developed for Grand Falls was used to produce 3D models of the Mactaquac Unit #5 discharge ring and draft tube walls. The deliverable for the discharge ring is a 1.4 billion point point cloud with a resolution less than a millimetre (Figure 28). Point clouds and meshes with image overlays of the draft tube walls were delivered for the draft tube with a maximum deviation of 3 mm from the survey control points (Figure 29). The deliverables are planned to be used in a CAD environment, although they could be delivered in the custom interface described in Chapter 5.

Figure 28 – Mactaquac Unit #5 discharge ring point cloud
The models accurately document the visual and spatial condition of the discharge ring and draft tube walls and support the motivation for testing the technology. Initial feedback from NB Power is positive and there is interest in continuing to use the photogrammetric inspection system. The main comment received is the desire to reduce the time to receive the deliverable so that decisions can be made during the current shutdown. Reductions in this time could be achieved with faster data acquisition by developing an automated data acquisition system, as well as additional computer resources to accelerate processing. The success of the models highlights the adaptability of the photogrammetric inspection system, especially considering the vastly different dimensions and configuration of the discharge ring and draft tube compared to the Grand Falls tunnel. The accuracy of the models supports that achieved with the Grand Falls tunnel and suggests that significantly higher accuracy is possible. The importance of an automated
data acquisition system to facilitate positioning the camera and to efficiently capture the images is evident.
8 Conclusions and Recommendations

A photogrammetric inspection system was developed to improve the traditional method of inspecting the Grand Falls Generating Station intake tunnel. The traditional inspection is visual based and deterioration is documented in spreadsheets and compiled in a report. Three main limitations were identified:

- difficulty visualizing deterioration and deterioration patterns throughout the tunnel,
- low accuracy in determining the location and size of defects, and
- the selectiveness and subsequent interpretation of an inspection.

The limitations identified in the traditional inspection make managing the Grand Falls intake tunnel challenging given decisions are based on a very limited data set. The traditional inspection has limited ability in documenting the true condition of the intake tunnel and is not a good basis for predicting future condition. Management and rehabilitation is thus challenging. Maintenance activities are difficult to prioritize, schedule, and allocate appropriate resources. Repairs are difficult to design, and contractors are ill-informed and must adapt to actual conditions to remain on schedule. The end result is inefficient lifecycle spending.

The goal of this study was to develop an inspection system to document the visual and spatial condition of the tunnel in a 3D model, integrating high resolution visual imagery and high accuracy spatial data. The photogrammetric inspection system consists of data acquisition, data modelling, and model delivery. Using the developed inspection system, a 3D model of the concrete-lined section of the Grand Falls intake tunnel was generated to improve rehabilitation planning. The success of the system at Grand Falls led to applying it at the Mactaquac
Generating Station in Unit #5 resulting in the generation of 3D models of the discharge ring and draft tube to support rehabilitation planning.

8.1 Conclusions

8.1.1 Data Acquisition

A data acquisition system, referred to as TIA, was designed and fabricated to facilitate camera positioning in the Grand Falls intake tunnel. Camera positioning was determined based on photogrammetric parameters to meet project objectives and constraints. TIA utilizes robotics to automate camera positioning and image capture. Over 5000 images of the 822 m concrete-lined section of the Grand Falls tunnel were captured with TIA over a period of seven days. There are many opportunities to reduce data capture effort, including lessons learned, additional TIAs, and redesigning TIA. Three data sets were collected:

- The entire concrete-lined section of the tunnel captured at a camera height of 5 m
- A 30 m high-resolution section captured at a camera height of 3 m
- An 8 m post-repair section captured at a camera height of 5 m

TIA significantly reduced the effort required to capture the images in the intake tunnel. It would not have been possible to manually capture the images required to produce a 3D model with the accuracy and resolution desired within the shutdown duration.

8.1.2 Data Modelling and Delivery

The images captured were processed to generate 3D models of the tunnel. A processing workflow was developed and refined that is largely automated and
verifies the ability to generate large scale photogrammetric models. There are critical processing inputs to ensure a high-quality model. Many software challenges were overcome due to the scale of the model. A 3D model of the entire concrete-lined section of the Grand Falls intake tunnel was generated with a visual resolution of 2 mm. The spatial accuracy of the model is 5 mm, which is the root mean square error between traditional survey check points and the model. Automated and manual processing time was four weeks and one week, respectively. Automated processing time is dependent on the number of images, image resolution, the processing resolution, and computer resources. Additional computer resources could be implemented to reduce the automated processing time. Models of the high-resolution section and post repair section were also generated. All models consist of point clouds for high accuracy spatial measurements and meshes with image overlays for high visual resolution.

With the assistance of the Faculty of Computer Science at UNB, a custom interface was developed using Unity 3D to facilitate model visualization and deliver an inspection-specific tool set. The interface permits visualization of large models on standard laptop computers. The main features of the interface are a console with location information, intuitive navigation, measurement capabilities, and side by side model comparison. The tool set can be expanded as required.

8.1.3 Traditional and Photogrammetric Inspection Comparison

The general asset management framework consists of four main activities: data acquisition, data analysis, development of deterioration models, and decision making. The models generated of the Grand Falls intake tunnel are a key component of the framework. By accurately documenting the actual visual and spatial condition of the entire concrete-lined section of the tunnel in a manner
that is easy to understand and communicate, the models allow a more detailed assessment of current and future condition, thus allowing more informed decisions and rehabilitation. Better managed assets have the potential benefits of reduced lifecycle spending, reduced risk of failure, and extended service life.

A conceptual comparison of the traditional and photogrammetric inspections was completed with respect to the speed of the inspection, cost, accuracy, ability to assess and predict condition, ability to plan rehabilitation, data analysis required after inspection, comprehensiveness, alternative uses, and likelihood of experiencing benefits of improved asset management. The time to create the final 3D model, which includes preparatory work, data capture, and post processing, is the main weakness of the photogrammetric inspection system. Should timing and data analysis after inspection not be urgent, the photogrammetric inspection system ranks better on all other compared parameters and delivers a superior deliverable at a comparable cost.

8.1.4 Mactaquac

Additional trials of the photogrammetric inspection system at the Mactaquac Generating Station were completed in the discharge ring and draft tube of Unit #5. A 1.4 billion point point cloud of the discharge ring was generated with a sub-millimetre resolution. The model will facilitate assessment of the turbine blade gap and cavitation. Point clouds and meshes with image overlays were generated of the bay walls in the draft tube. The models are a significant reduction in effort in comparison to the traditional method of documenting cracks and provide a superior deliverable that will allow accurate monitoring of crack progression. The success of the photogrammetric inspection system at the Mactaquac Generating Station demonstrates the adaptability of the
photogrammetric inspection system to environments with different configurations and dimensions.

8.2 Contributions

Contributions as a result of this research are summarized in the following sections.

8.2.1 Data Acquisition System

A photogrammetric data acquisition system was developed to capture images in large unlit hydroelectric tunnels. The following points summarize the contribution of the data acquisition system.

• Identification and documentation of the functional requirements of the photogrammetric data acquisition system to capture images, which include the frame, photography and lighting equipment, rotational and longitudinal movement, and electronics and controls to automate image capture.

• The design, fabrication, testing, and refinement of the photogrammetric data acquisition system that can be built upon and further refined to facilitate capturing images of a variety of infrastructure.

8.2.2 Data Modelling and Delivery

High resolution and high accuracy photogrammetric models were generated and delivered to facilitate rehabilitation planning of the Grand Falls intake tunnel. Contributions related to data modelling and model delivery are summarized in the following points.
• Verification of photogrammetry as a viable modelling tool for large scale underground infrastructure, as well as the ability to achieve high accuracy and high resolution large scale models.

• The vision and design of an interface with an inspection-specific tool set to visualize and interact with 3D models, as well as guidance during its implementation, that can be built upon and further expanded.

• A 3D model of the Grand Falls intake tunnel that enhances visualization and communication of deterioration, and therefore management of the asset.

• 3D models of the Mactaquac Unit #5 discharge ring and draft tube bay walls, which enhance visualization and communication of deterioration, and therefore management of the asset.

8.3 Value of the Research

The following points reinforce the value of the photogrammetric inspection system.

• The photogrammetric inspection system developed to model the Grand Falls intake tunnel was done in collaboration with NB Power to meet their specific needs and solve a problem they identified as significant.

• NB Power has given very positive feedback on the practical and potential application of the model to support rehabilitation planning and management of the asset.

• The 3D model of the Grand Falls intake tunnel generated interest from other groups at NB Power and led to a trial of the photogrammetric inspection system at the Mactaquac Generating Station to produce 3D models of the Unit #5 discharge ring and draft tube. Feedback on the
models has been positive and there is interest in continuing to use the photogrammetric inspection system.

- The author was invited to give a presentation on the research to a group of international utility owners and consultants on behalf of NB Power at the Centre for Energy Advancement through Technological Innovation (CEATI) Hydropower 2018 conference in Tucson, Arizona, which was well received.

- Following the CEATI Hydropower 2018 conference, the presentation was given to NB Power senior management, who saw significant value in the photogrammetric inspection system and were enthusiastic about using it at a variety of NB Power facilities, and resulted in plans to give the presentation to the NB Power executive.

8.4 Recommendations
The following sections summarize recommendations for how researchers could build on this research, how NB Power could continue to use the research, and how industry could prepare for adoption.

8.4.1 Researchers
- One of the most challenging activities of the photogrammetric inspection system is capturing images in an efficient manner. TIA facilitated image capture in the Grand Falls intake tunnel and there are several areas for improvement to further reduce the effort required to capture images. Improvements are likely with further automation and faster photography equipment. Aerial platforms also pose an opportunity to reduce effort but will require indoor positioning, as well as smaller and lighter photography equipment.
• TIA is a one-off design made specifically for capturing images of the Grand Falls intake tunnel and is not easily adapted to other facilities with different dimensions and configurations. It is recommended that a multipurpose automated data acquisition system be developed that can adapt to various dimensions and configurations.

• A comprehensive comparison of the traditional and photogrammetric inspections should be conducted to assess the differences in documented deterioration. The traditional inspection could be digitized, and deterioration compared to the model for a detailed assessment.

• The 3D models facilitate visualization of deterioration, although deterioration must still be identified manually. Inspection and condition assessment could be improved with automated deterioration detection and quantification. Computer vision algorithms should be assessed and added to the interface tool set. Other inspection-specific tools should also be identified.

• The photogrammetric inspection system generates a significant amount of data. Data storage and management will become an important issue over the long term as this type of inspection is adopted. It is recommended that data storage and management be studied, and protocols developed to ensure integrity over the long term.

• The photogrammetric inspection system was developed specifically for the hydroelectric intake tunnel at Grand Falls. The photogrammetric inspection system may be suited to inspecting other underground environments, such as mines or transportation tunnels. It is recommended that other potential fields be investigated.
8.4.2 NB Power

- Feedback from NB Power on the Grand Falls intake tunnel model has been positive, although thorough use of the 3D model has not yet occurred. It is recommended that NB Power conduct an inspection based on the 3D model and evaluate the use cases identified, as well as other potential use cases.

- Upon completing a thorough inspection of the Grand Falls tunnel based on the 3D model, NB Power should consider how to proceed with the photogrammetric inspection system, either with additional pilot studies or formal adoption.

- Additional pilot studies with the photogrammetric system should be completed at other NB Power facilities to further assess the adaptability of the system. Pilot studies could be conducted in collaboration with researchers and include the exploration of a multipurpose data acquisition system.

- A cost benefit analysis should be completed to quantify the value of the photogrammetric inspection system and assess if the system permits a reduction in lifecycle spending and an increase in service life. Quantifying the value of the photogrammetric inspection system will be challenging as there are many new benefits that are not directly comparable with the traditional inspection.

8.4.3 Industry

- Industry should be prepared to adopt and explore more advanced inspection methods to improve management of their assets. Pilot programs
could be implemented to assess needs and the capability of various technologies in meeting them.

- A limited amount of literature was identified regarding the inspection of hydroelectric tunnels. Owners, consultants, and researchers are encouraged to publish their work to expand knowledge and advance the industry.

- Best practices should be monitored to assess state of the art technology, which could provide a competitive advantage in a current market or lead to the exploration of new ones.

- Industry standards should be updated as new technology is developed and adopted to ensure the industry advances as a whole.
9 References


New Brunswick Power Corporation. 2001. Units 5 and 6 Dimensional Montiroing
Parameters. Drawing # 0675-40000-7000-001-GA-E-00.


Appendix A – TIA Evolution
The design of TIA occurred over several weeks. There were five major iterations before arriving at the version that was fabricated for the Grand Falls intake tunnel inspection. This Appendix describes the major iterations. An isometric image of each iteration is provided for visual reference (Figures 30-34). The drawing package produced by Jeremy Bowmaster for the final design follows.

The first design iteration was purely conceptual and without design calculations to visualize the required camera positioning and anticipate structural requirements. The design was based on a rectangular horizontal frame with two wheels located at the boom end and two legs at the other end. Handles allowed the frame to be lifted and rolled. Two vertical frames were designed to support the boom and drive shaft, which extended the length of the horizontal frame. This drive shaft design was chosen as high loads were anticipated in the bearings due to the length of the boom. The vertical frames included both ridged and cable support. The second iteration included additional reinforcing and ridged support in place of the cable to reduce movement during boom rotation and mitigate image blur. Outriggers were added in this iteration for stabilization during image capture. All terrain tires were also added in place of the smooth tires to accommodate rough terrain and anticipated gravel and sand deposits. Two wheels were added during the third design iteration to avoid lifting the frame during movement. The additional support added in the second iteration added a significant amount of weight. Design calculations were completed during the fourth and fifth design iterations to assess structural requirements and displacements. Unnecessary support was removed, which resulted in a significant reduction in weight. The design transitioned from four to three wheels to increase stability. A three-wheeled design allows all wheels to remain in contact with the ground on uneven terrain. The rear vertical frame was removed as it was
unnecessary to support the drive shaft. Smooth tires were selected for the final design to facilitate movement along the length of the tunnel after confirming gravel and sand deposits were unlikely.

Figure 30 – TIA design iteration 1

Figure 31 – TIA design iteration 2
Figure 32 – TIA design iteration 3

Figure 33 – TIA design iteration 4
Figure 34 – TIA design iteration 5
Appendix B – TIA Code
```cpp
#include <AccelStepper.h>
#include <SoftwareSerial.h>

SoftwareSerial swSer(2, 3);

// Define some steppers and the pins they will use
AccelStepper stepper1(1, 8, 9);
const int LED = 13;
const int Go = 12; // pin of button to trigger motor
const int Ena = 11;
const int CW = 7;
const int CCW = 6;
int i;
long pos = 10664;
int inc;

void setup()
{
    Serial.begin(57600);
    swSer.begin(57600);
    pinMode(LED, OUTPUT);
    pinMode(Go, INPUT_PULLUP); // initialize button pin as input
    pinMode(Ena, INPUT_PULLUP);
    pinMode(CW, INPUT_PULLUP);
    pinMode(CCW, INPUT_PULLUP);
    stepper1.setCurrentPosition(0);
    stepper1.setEnablePin(10);
    stepper1.setMaxSpeed(3000);
    stepper1.setAcceleration(500);
    stepper1.setMinPulseWidth(20);
}

void loop()
{
    // Disable power to motor and stop
    stepper1.disableOutputs();
    stepper1.stop();

    // Allow controls while enable button pushed
    while (digitalRead(Ena) == LOW)
    {
    }

    // Enable power to motor and start
    stepper1.enableOutputs();
    stepper1.start();
    stepper1.step();

    // Check button status
    if (digitalRead(Go) == HIGH)
    {
        pos += inc;
    }
    else
    {
        pos -= inc;
    }
    
    // Send position to serial
    Serial.print(pos);
    Serial.print("\n");
}
```

Stepper Motor
void Controls() {

    // Enable power to motor and set acceleration and speed
    stepper1.setCurrentPosition(0);
    stepper1.enableOutputs();
    i = 1;
    inc = 1;

    // If Go button pushed, rotate 360 degrees
    if (digitalRead(Go) == LOW) {
        Camera();
    }

    if (digitalRead(CW) == LOW) {
        JogCW();
    }

    if (digitalRead(CCW) == LOW) {
        JogCCW();
    }

}

void Camera() {

    while (i < 15 && (digitalRead(Ena) == LOW)) {
        stepper1.runToNewPosition(pos*inc);
        delay(2000);
        digitalWrite(LED, HIGH);
        digitalWrite(LED, LOW);
        swSer.print('1');
        swSer.print('n');
        delay(800);
        i++;
        inc+=2;
    }

    if (i = 15 && (digitalRead(Ena) == LOW)) {

inc++;  
  stepper1.runToNewPosition(298598);
}

void JogCW()
{
  stepper1.move(-1000000);

  while (digitalRead(CW) == LOW && (digitalRead(Ena) == LOW)) {
    stepper1.setSpeed(3000);
    stepper1.runSpeedToPosition();
  }
}

void JogCCW()
{
  stepper1.move(1000000);

  while (digitalRead(CCW) == LOW && (digitalRead(Ena) == LOW)) {
    stepper1.setSpeed(3000);
    stepper1.runSpeedToPosition();
  }
}
#include <ESP8266WiFi.h>
#include <ESP8266WebServer.h>
#include <WiFiClient.h>
WiFiServer server(80);

#include <SoftwareSerial.h>
SoftwareSerial esp(12, 14);

const char* ssid = "ESPap";
const char* password = "thereisnospoon";
const char* host = "192.168.4.1";
int data_outgoing = 0;
int i = 0;
int camera = 4;

void setup() {
    pinMode(camera, OUTPUT);
    digitalWrite(camera, HIGH);
    Serial.begin(57600);
    esp.begin(57600);
    WiFi.mode(WIFI_AP);

    if (!WiFi.softAP(ssid, password)) {
        Serial.println("Failed to create access point!");
        while (true);
    }

    server.begin();
}

void loop() {

    WiFiClient client;
    String data = "0";
    int attempts = 0;

    client = server.available();

    if (!client) {
Serial.println("No clients connected!");
delay(1000);
return;
}

Serial.println("Client connected...");

while (client.connected()) {

data = esp.readStringUntil('n');
Serial.print(data);

switch (data[0]) {
    case '1':
        client.print(1);
        break;

    default:
        client.print(0);
        break;
}

    client.flush();
}

Serial.println("Client disconnected!");
client.stop();
}
Wi-Fi – Client

```cpp
#include <ESP8266WiFi.h>
#include <ESP8266WebServer.h>
#include <WiFiClient.h>

const char* ssid = "ESPap";
const char* password = "thereisnospoon";
const char* host = "192.168.4.1";
int port = 80;
int camera = 4;
int data;

void setup(){
  pinMode(camera, OUTPUT);
  digitalWrite(camera, LOW);
  Serial.begin(57600);
  delay(10);
  Serial.println("Started...");
  WiFi.mode(WIFI_STA);
}

void loop() {
  WiFiClient client;
  int wifiStatus;
  int i;
  int attempts = 0;

  if (WiFi.status() != WL_CONNECTED) {
    Serial.println("Connecting to WiFi...");

    WiFi.begin(ssid, password);

    while (WiFi.status() != WL_CONNECTED && attempts < 15) {
      attempts++;
      delay(1000);
    }

    if (WiFi.status() != WL_CONNECTED) {
      Serial.println("Failed to connect to WiFi!");
      delay(1000);
      return;
    }
```

```
Serial.println("WiFi connected!");
Serial.println("Connecting to host...");

if (!client.connect(host, port)) {
    Serial.println("Failed to connect to host!");
    delay(1000);
    return;
}

Serial.println("Connected!");

while (client.connected()) {
    if (client.available()){

        data = client.read();
        //Serial.print(data);

        switch (data) {

        case 49:
            digitalWrite(camera, HIGH);
            delay(10);
            digitalWrite(camera, LOW);
            break;

        default:
            digitalWrite(camera, LOW);
            break;
        }

    }

}

Serial.println("Disconnected from server!");
client.stop();
delay(1000);
Curriculum Vitae

Candidate's Full Name: David Cody Bradley

Universities Attended: University of New Brunswick
Fredericton, New Brunswick
Bachelor of Science in Civil Engineering (First Division)

Publications:


Conference Presentations:

