Building Tomorrow's Society
Bâtir la Société de Demain

Fredericton, Canada
June 13 – June 16, 2018/ *Juin 13 – Juin 16, 2018*

PHOTOGRAMMETRIC MODELLING OF THE GRAND FALLS HYDROELECTRIC GENERATING STATION

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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 shutdown once every four years for only a few days to perform visual inspections and maintenance of the intake tunnel. The tunnel measures 7.5 m in diameter and travels underneath a portion of the town for approximately 921 m before reaching the turbines. 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 generate and distribute 3D models of the intake tunnel. A semi-automated data acquisition system was designed to facilitate data capture. Approximately 5000 images of the entire 822 m concrete-lined section of the tunnel were taken during a two-week scheduled shutdown. The images were processed and combined with traditional surveying to generate a model with a visual resolution of 2 mm and a spatial accuracy of 5 mm. A custom interface is being developed to interact with the models and provide users with an inspection-specific tool set. The models will provide valuable information for future engineering assessments, job planning, contracting, repairs, scheduling and the location of potential future development of hydro in Grand Falls.

1 Introduction

The Grand Falls Generating Station was constructed in the late 1920's 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. The intake 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 diameter. Figure 1 provides a plan view of the generating station intake tunnel overlaid on a google earth aerial image.

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 (NB Power 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. Observations are documented in spreadsheet form and include the longitudinal and clock location, size, and remarks on the deterioration (NB Power 2004, SNC-Lavalin Inc 2007, 2008, 2013). The types of deterioration documented 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. The inspection method 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 the location and size of defects, and the selectiveness and subsequent interpretation of an inspection.

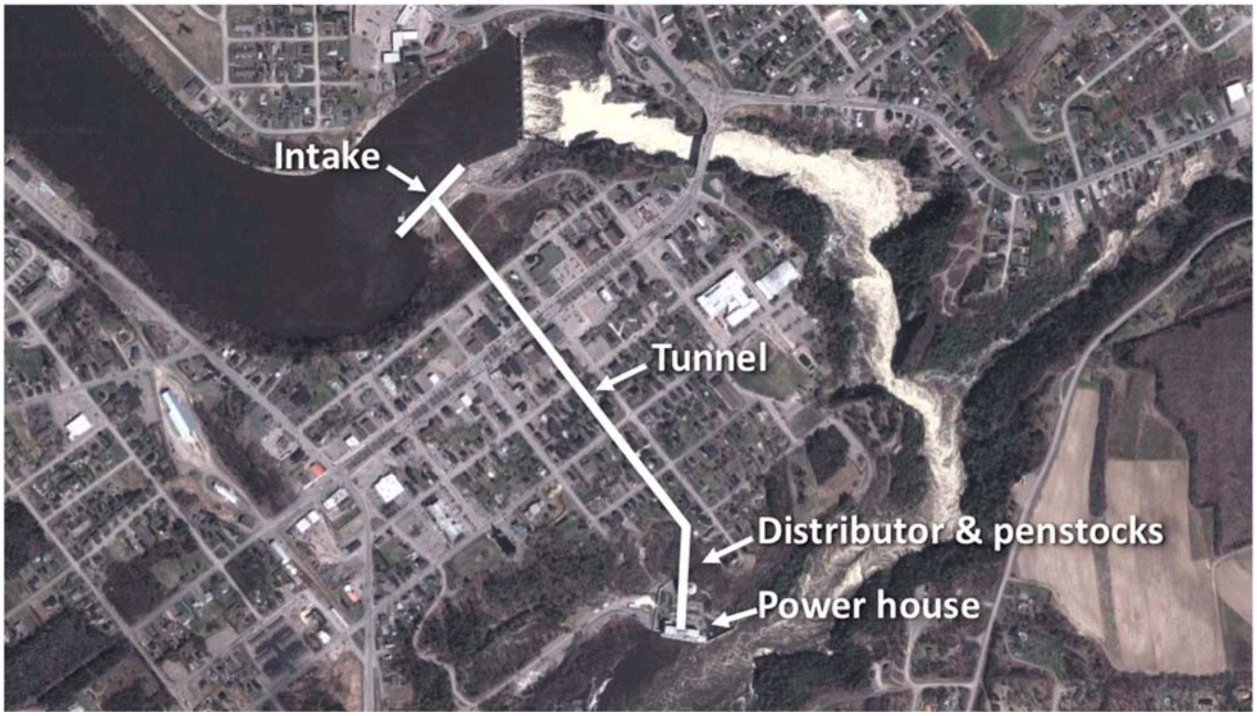


Figure 1: Sketch of the Grand Falls Generating Station intake tunnel

The 2012 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 and undocumented. 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 current inspection method given it is conducted standing on the invert of the tunnel. Defects on the ceiling of the tunnel could 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 will be required will be difficult without a good sense of the deterioration trends.

The current inspection method is inherently selective in nature. An inspector documents defects that they notice and types of deterioration 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 subsequent expert is also required to interpret the condition of the tunnel based on what was documented during the inspection. The condition assessment therefore has a high level of subjectivity.

The limitations identified in the traditional inspection method make managing the Grand Falls intake tunnel challenging. Management decisions are based on a very limited data set. The traditional inspection method 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.

The current method of inspecting the Grand Falls intake tunnel is consistent with the common inspection techniques found in the literature for hydroelectric tunnels. Inspecting hydroelectric tunnels is largely a manual task relying on visual observations documented in tabular form (Wang and Lee 2013, Ganse et al. 2016, Shelton et al. 2016). More advanced inspection methods are beginning to be explored. Mohta et al. (2016) demonstrate that the visual and spatial condition of penstocks can be documented autonomously with an unoccupied aerial vehicle (UAV), although there are some significant limitations that need to be overcome to create a viable and consistent inspection method.

1.1 Photogrammetric Inspection

An improved inspection system was developed in consultation with NB Power for the upcoming shutdown planned for August 2017. The overarching purpose 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. Visual and spatial documentation are considered equally important, and each provide unique information that describes the condition of the tunnel. Several 3D scanning technologies that could be adopted to hydroelectric tunnel inspections were assessed. Candidates include stationary LiDAR, mobile LiDAR, and photogrammetry. 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 of 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, although capturing images suitable for photogrammetric modelling in indoor environments is complex and requires positioning the camera in potentially difficult to reach areas. Supplemental lighting is also required. Photogrammetry is typically not used in large indoor environments as a result.

Photogrammetry was chosen as the capture technology as it has the ability to deliver high resolution visual imagery, as well as high spatial accuracy. A major challenge in capturing the images required to build a photogrammetric model is positioning the camera efficiently and maintaining the required overlap between images and distance from the surface. Some type of data acquisition system will be required to facilitate positioning the camera throughout the tunnel. Several constraints were identified that further complicate data collection. The most significant constraint is the planned duration of the shutdown. The shutdown is scheduled for a two-week period at the end of August. A few days of the shutdown are required for dewatering and watering back up. The inspection can proceed during the remainder of the shutdown and should not conflict 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. 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.

2 Tunnel Inspection Assistance Design

Images are the foundation of a photogrammetric 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 is perpendicular to the surface being captured. Maintaining a consistent height from the surface is also important as it affects the ground sampling distance (GSD) and therefore the resolution of the model. This term arises from aerial photography where the GSD is defined as the distance between pixel centers measured on the ground. 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 2. 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.

2.1 Photogrammetric Parameters

Photogrammetric parameters are the main constraint on the details of positioning the camera and also dictate the number of images that will be required, thus directly influence the length of time required for data capture. The primary consideration is the GSD as it has a large influence on the accuracy and resolution of the resulting model. Changing the GSD is achieved by changing the size of the pixels on the sensor, the height of the camera above the surface, and the field of view of the camera. 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.

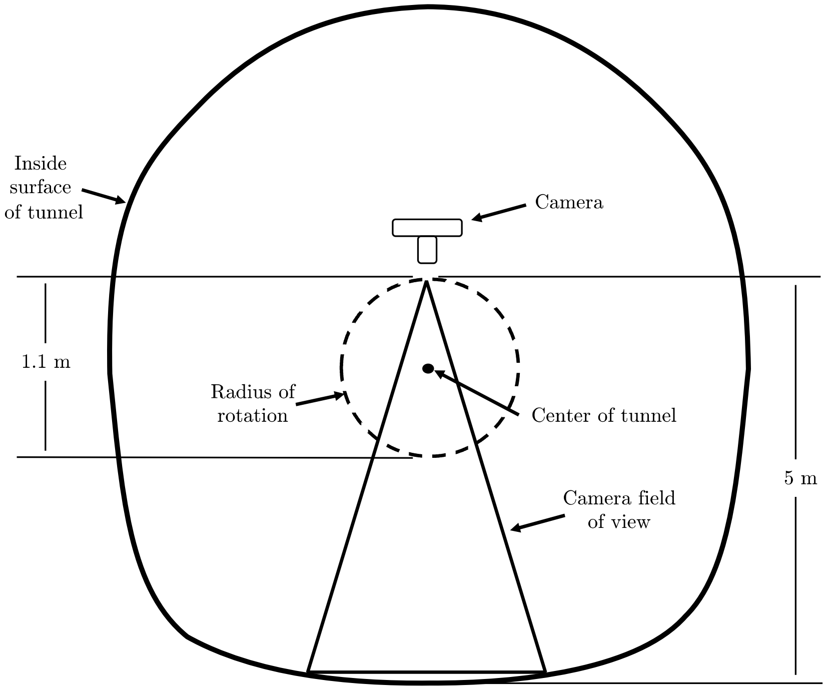


Figure 2: Illustration of the required camera position and rotation

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 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 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 photogrammetric 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. 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 2018, Pix4D 2018).

Preliminary estimates of the number of images required to capture the entire 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: a 5 m camera height, a 20 mm focal length rectilinear lens, a 1.6 mm GSD, and an 80% primary and 60% secondary overlap. The rotational axis is chosen as the primary overlap to minimize the number of longitudinal stations. The photogrammetry parameters require 13 images throughout the rotation to provide an 80% overlap. The secondary overlap is the longitudinal length of the tunnel. A spacing of 4.2 m longitudinally provides a 60% overlap.

2.2 Tunnel Inspection Assistant Design

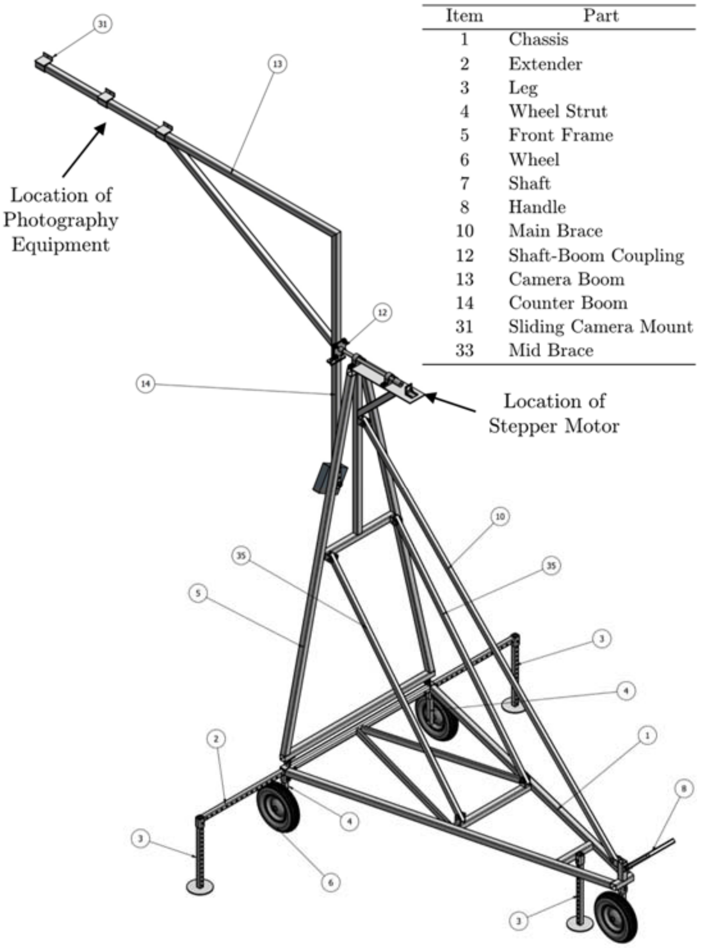
Collecting high quality images throughout the 822 m concrete lined section within the shutdown period is a significant challenge. Positioning the photography equipment as illustrated in Figure 2 within the estimated time of four days requires some type of mechanical assistance. A tunnel inspection assistant (TIA) was designed and fabricated to facilitate data capture. The main components of TIA include the frame, 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.

2.2.1 TIA Frame

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 HSS aluminum tubing. 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 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. 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. 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. A schematic of the frame is presented in Figure 3.

2.2.2 Electronics and Controls

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



Item	Part
1	Chassis
2	Extender
3	Leg
4	Wheel Strut
5	Front Frame
6	Wheel
7	Shaft
8	Handle
10	Main Brace
12	Shaft-Boom Coupling
13	Camera Boom
14	Counter Boom
31	Sliding Camera Mount
33	Mid Brace

Figure 3: Schematic of the TIA frame

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 preprogramed to perform specific actions with the stepper motor and camera trigger based on inputs from the control panel. The control panel has five push buttons associated with the microcontroller and is located on the long brace near the handle for easy access.

A start button initiates a program to begin semi-autonomous 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.

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. A 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 with a 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.

2.2.3 Lighting Equipment

Lighting is required for a proper exposure with ISO, aperture, and shutter settings suitable for photogrammetry. Flash lighting is used rather than continuous lighting due to the greater light output and lower power requirements. 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 keypoint 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 of 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.

3 Data Acquisition

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 collection began on Wednesday, September 22nd and continued until Monday September 27th, at which time the entire 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 September 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 September 25th. Figure 5 is an image of TIA capturing images in the 3 m configuration.

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. 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.

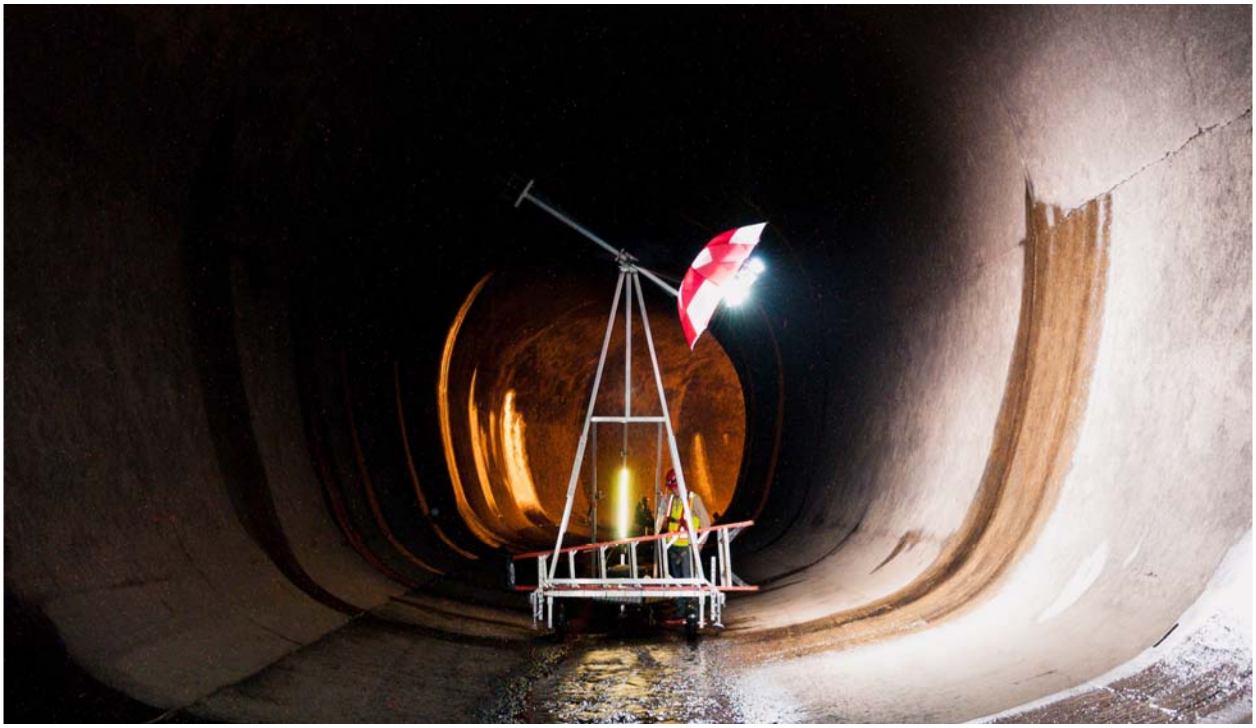


Figure 4: Image of TIA capturing images in the 3 m configuration.

The scanning process involved positioning TIA at a station, capturing that section of the tunnel, and advancing 4.2 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. 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 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.

Over 5000 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 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.

4 Models

The process of generating photogrammetric models requires several steps and can be very time consuming. A processing workflow was developed that is largely automated, with key inputs required at each step to ensure a high-quality model. Dense point clouds as well as meshes with an image overlay were generated 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 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. The combination of dense point clouds and meshes provides models of the entire Grand Falls intake tunnel that deliver a visual resolution of 2 mm and a spatial accuracy of 5 mm. Accuracy is defined as the route mean square (RMS) deviation of the model from survey check points that were not used for image alignment. The accuracy of the survey control and check points is estimated to be 40 mm. Automated and manual processing time to generate meshes with image overlays was 4 weeks and 1 week, respectively. Additional computer resources can be used to reduce automate processing time. To reduce the substantial computer resources required to process large scale photogrammetric models, the tunnel was processed in several smaller segments. Figure 5 is an image of the 822 m point cloud generated.

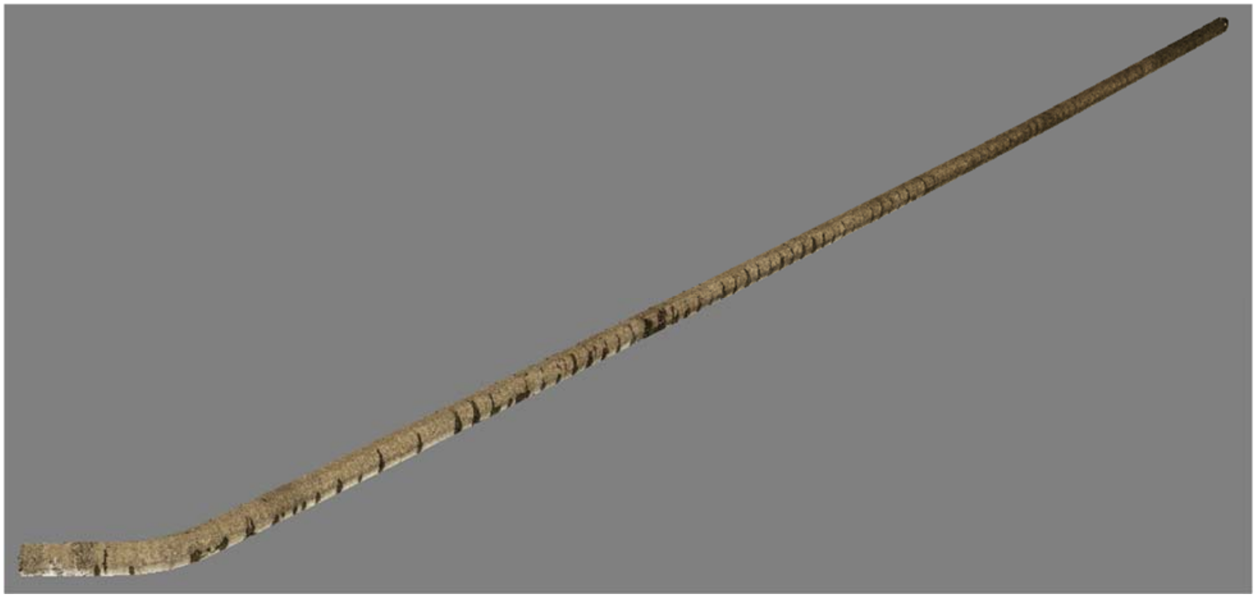


Figure 5: Point cloud of the entire Grand Falls tunnel

A custom interface is being developed to interact with the models and provide an inspection-specific tool set. The main features of the interface include the ability to navigate very large models on standard laptop computers, intuitive navigation, measurement capabilities, 3D annotation, and multiple model comparisons within a split screen window. The interface is expandable and new features can be added as need arises.

5 Conclusion

The traditional method of inspecting the Grand Falls Generating Station intake is visual based. Deterioration is documented in spreadsheets and compiled in a report. Three limitations were identified with the traditional inspection method. The inspection is difficult to visualize, inaccurate, and selective. The limitations identified in the traditional inspection method make managing the Grand Falls intake tunnel challenging given decisions are based on a very limited data set. The traditional inspection method 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.

A photogrammetric inspection system was developed to improve the traditional method of inspecting the Grand Falls Generating Station intake tunnel and facilitate rehabilitation planning. A data acquisition system, referred to as TIA, was designed and fabricated to facilitate camera positioning. 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. 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. The 3D models generated accurately document the actual visual and spatial condition of the entire tunnel in a manner that is easy to understand and communicate. The models document the entire tunnel, rather than only the items identified by the inspector, and allow additional specialized experts to interpret the condition of the tunnel. Accurate assessments of current and future condition are now possible allowing more informed decisions, thus better management of the tunnel.

Acknowledgements

Thanks to New Brunswick Power for the research opportunity, Jennifer Day for the data collection assistance, the University of New Brunswick technicians for the fabrication assistance, and Scott MacDonald for proposing the initial research idea.

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