

# RECLAMATION

*Managing Water in the West*

## Photogrammetric Tools for Condition Assessment of Reclamation Structures, Part 2

Technical Memorandum No. 8530-2016-27  
Research and Development Office  
Science and Technology Program  
(Final Report) ST-2016-9384-01



U.S. Department of the Interior  
Bureau of Reclamation  
Research and Development Office

August 2016

## **Mission Statements**

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
T1. REPORT DATE Aug. 2016		T2. REPORT TYPE Research		T3. DATES COVERED	
T4. TITLE AND SUBTITLE Photogrammetric Tools for Condition Assessment of Reclamation Structures, Part 2				5a. CONTRACT NUMBER 16XR0680A1-RY1541IS201619384	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 1541 (S&T)	
6. AUTHOR(S) Matthew Klein, PE, PhD mjklein@usbr.gov 303.445.2368				5d. PROJECT NUMBER 9384	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER 86-68530	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Concrete, Geotechnical and Structural Laboratory U.S. Bureau of Reclamation PO Box 25007, Denver CO 80225				8. PERFORMING ORGANIZATION REPORT NUMBER 8530-2016-27	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research and Development Office U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007				10. SPONSOR/MONITOR'S ACRONYM(S) R&D: Research and Development Office BOR/USBR: Bureau of Reclamation DOI: Department of the Interior	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) ST-2016-9384-01	
12. DISTRIBUTION / AVAILABILITY STATEMENT Final report can be downloaded from Reclamation's website: <a href="https://www.usbr.gov/research/">https://www.usbr.gov/research/</a>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT: This report summarizes a continuation of research begun in 2015 to outline advanced photogrammetric techniques for evaluation and implementation in Reclamation's 3D condition assessment program. The tools investigated in this report include the use of spherical cameras for photogrammetric data collection in interior locations and the use of virtual reality as an intuitive method to view, navigate and interact with photogrammetric 3D models.					
15. SUBJECT TERMS: photogrammetry, spherical camera, virtual reality, augmented reality, condition assessment, inspection					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  U	18. NUMBER OF PAGES 24	19a. NAME OF RESPONSIBLE PERSON Matthew Klein
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER 303-445-2125

S Standard Form 298 (Rev. 8/98)  
P Prescribed by ANSI Std. Z39-18

# PEER REVIEW DOCUMENTATION

## Project and Document Information

Project Name: Photogrammetric Tools for Condition Assessment of Reclamation Structures, Part 2

WOID: Z9384

Document: Final Report ST-2016-9384-01

Document Author(s): Matthew Klein

Document date: August 2016

Peer Reviewer: Kurt von Fay

## Review Certification

**Peer Reviewer:** I have reviewed the assigned items/sections(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewer \_\_\_\_\_  
(Signature)

## Executive Summary

This report describes the second year of work done for this two year project. It focused on collecting and processing data using spherical cameras and viewing the 3D model using virtual reality (VR) headsets.

This work was part of the larger project to investigate advanced photogrammetric techniques related to structural analysis, remote monitoring, and condition assessments of Reclamation structures. Photogrammetry has demonstrated benefits for:

- Inspections
- Quantifying extent of damage
- Identifying seepage
- Identifying amount of corrosion
- Mapping locations and generating topography
- Measuring volumes
- Determining movement
- Comparing time-based changes
- Archival record keeping

In short, photogrammetry promises significant improvements for many steps in the inspection and condition assessment of Reclamation structures.

However, several challenges have been identified to implementing this technology for Reclamation. Investigations were planned and some have been conducted to assess possible solutions. This project received funding in Fiscal Year 2015 (FY15) to continue work to advance Reclamation's knowledge and expertise in the following areas:

- 4D Photogrammetry: a series of simultaneous images captured at regular intervals to produce a time-based 3D model
- Georeferencing: adding global coordinates to the 3D model for scaling and positioning
- Low Cost Point-and-Shoot and Smartphone Sensor Usage: successfully creating 3D models using small and inexpensive sensors such as those found in point-and-shoot cameras and smartphones
- Non-visible Light Photogrammetry: 3D models with an infrared (IR) texture to reveal subsurface defects in concrete
- Client Software for Viewing 3D Models: Allows users to view and manipulate the 3D model without purchasing additional software or advanced hardware
- Inspections: Using the 3D model to provide a structural inspection in areas where the inspector may have difficult or no access
- Measuring Extent of Damage: Providing lengths, widths, areas, volumes and movements for cracks and spalls and other types of physical defects
- Identifying Seepage or Corrosion: Employing feature extraction techniques to classify points with seepage or corrosion characteristics

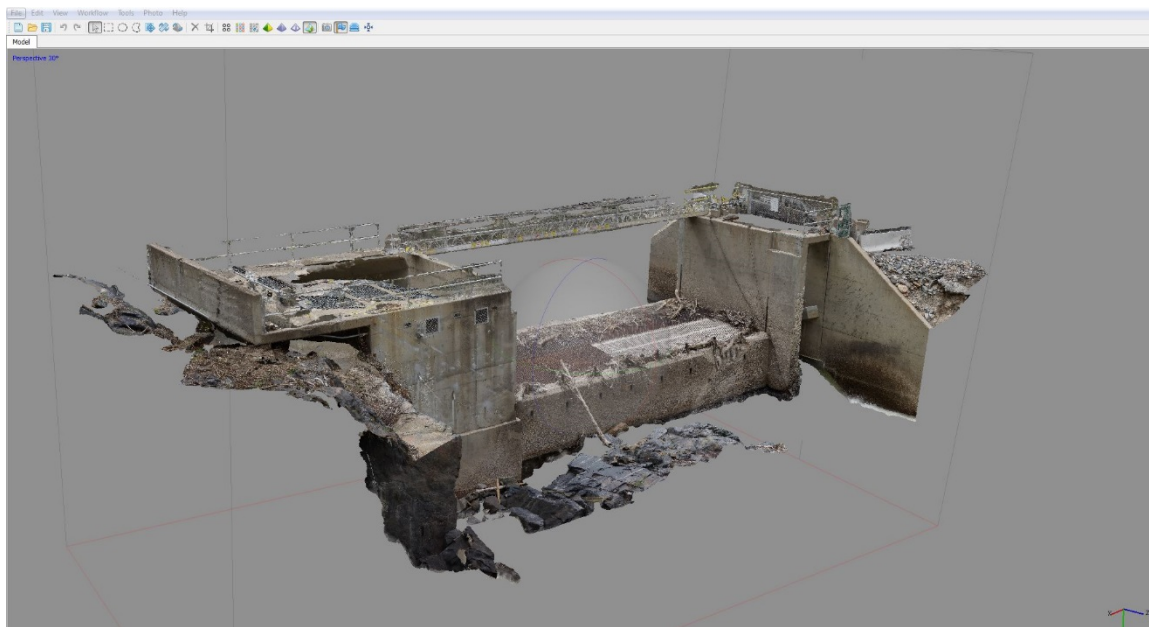
# Contents

Executive Summary .....	v
Introduction.....	2
Photogrammetric Tools .....	5
Spherical Cameras .....	5
Virtual Reality.....	11
Conclusions.....	16
References .....	<b>Error! Bookmark not defined.</b>

# Introduction

In FY2015, the research office funded the first part of this project to research advanced photogrammetric techniques for evaluation and analysis of Reclamation structures [1]. Photogrammetry has been studied and used at Reclamation for several years. The initial work was begun by the geology group to analyze rock foundations and slope stability. Recently, photogrammetry has been considered by the Concrete, Geotechnical and Structural Laboratory as a cost effective solution for condition assessments of the various concrete and earthen structures throughout Reclamation.

Photogrammetry is the science of using a series of images to solve for the positions of individual points within a scene. The images are usually taken of the subject using a systematic procedure where adjacent images overlap by about 60% and the entire scene is blanketed with a grid of images. The images are digitized and then analyzed by computer software to solve for the position of individual pixels. This information is used to generate a point cloud – a collection of data points with coordinate information. Depending on the final product, the point cloud can be meshed and textured with the image overlay to give a photorealistic three-dimensional (3D) representation of a feature or structure. This 3D representation is frequently called a model of the structure (see Figure 1). When the point cloud is properly scaled or georeferenced, the model can be used to make measurements of its physical features. When used in combination with infrared or multispectral sensors, additional information about the structure can be overlaid on the 3D model.



**Figure 1: Example of Photogrammetric 3D Model**

3D condition assessment using photogrammetry also provides a method to gather information about hard-to-access or inaccessible features. In addition, once the data is collected, the modeling and analysis, including condition assessment can occur from the convenience of the

office without safety, weather, or time delays. Finally, since the model is digital, it can be stored for future analysis or comparison to models created at different times.

While photogrammetric models can be generated from traditional frame and fisheye type cameras, the models can also be generated from spherical and cylindrical camera images. Spherical and cylindrical cameras capture images entirely around the camera using two or more sensors and fisheye lenses to capture 360 degrees of the scene. These are advantageous over conventional cameras when capturing images for interior models such as rooms, tunnels or shafts. . When a cylindrical or spherical camera is used in, for example, a room, the theoretical minimum number of images required to solve the position of each point in the room is three. Attention to the proper overlap is not required since all 360 degrees of the subject is captured in each image.

As described earlier, photogrammetry requires a minimum of 60 percent overlap between adjacent pictures to allow for a minimum of projecting the same point on at least three images to solve for that point's location. This overlap is followed throughout the model to blanket the subject with a grid of images. This procedure works best for subjects with a length and width much greater than the depth.

In order to develop a model of an interior surface, such as a cubic room, overlapping images are required for each of the six walls. Each plane is captured best if the camera sensor is parallel to the surface. To tie each plane to each other, images capturing the transition to the adjacent plane are required at intermediate angles. The maximum angle between adjacent planes that is usually sufficient to tie angled surfaces is 22.5 degrees. For example, two planes at 90 degrees rotation from each other require tie images at 22.5, 45, and 67.5 degrees. In an interior room with six planes, photogrammetry will require sufficient images to fully solve each plane as well as the intermediate tie image sets between each plane. For a simple room, this equates to a minimum of 6 planes with 3 images and 8 vertices with 3 intermediate tie angles for a total of 48 images.

To understand the 3D model generated by photogrammetry in, for example, the commercially available Agisoft PhotoScan Professional, the photogrammetric process used in the software should be understood. Since Agisoft PhotoScan Professional is a commercial product, many of the algorithms are proprietary but the basic process is simple. First, unique points in the images are detected using a process related to the scale-invariant feature transform or SIFT algorithm. The camera positions are solved and refined using a bundle-adjustment algorithm which is essentially a nonlinear least squares function. The point cloud is created by giving positions in 3D space to points from the overlapping images (pair-wise depth map computation) that were used to solve for the camera positions during the initial photogrammetric processing. A mesh is created by fitting connected surfaces, faces or triangles to the point cloud data. The mesh can also be rendered as lines referred to a wiremesh. Finally, a photorealistic texture is applied to the meshed model by blending the source images to provide a realistic rendering of the model [1]. The resolution of the texture is related to the initial resolution of the image.

Once the 3D model is completed there are several ways to interact with the model. The model can be viewed in the native software that it was created in such as Agisoft Photoscan Professional. It can also be exported to a variety of software packages that allow for viewing and manipulation. Many computer aided design (CAD) applications can support point cloud and



mesh viewing. In some of these applications the texture is not rendered or imported and only the wiremesh or shaded models are displayed. Some of the applications support anaglyph and/or hardware 3D stereoscopic displays. These displays simulate a 3D view of the model using special viewing glasses and other hardware such as 3D capable monitors and infrared emitters for syncing the refresh rates between the monitor and glasses. There are also websites where the models can be uploaded, so that others can view the model from any computer with internet access. Recently, the ability to view the models in 360 degree 3D that has been made possible using either a smartphone powered headset or a headset that is connected to the computer using special software. This headset solution is known as virtual reality or VR.

Virtual reality is basically an immersive digital environment. The user is entered into the environment by the use of a wrap-around headset that features a separate display for each eye. The headset may or may not require feature sound. Panning throughout the environment is accomplished by simply turning your head. In order to move to a different location in the environment or to otherwise interact with the model, a handheld controller is typically required. The types of interactions available are limited to the software developers feature set. Based on available apps and popular interest, virtual reality is mostly used for entertainment (gaming) but is also used for virtual tours and 360 degree pictures and video. However, several engineering firms have been recently featured in Civil Engineering magazine for their implementation of VR technologies in their design workflow including Leslie E. Roberson Associates (LERA), NBBJ, and AECOM (in collaboration with Trimble Navigation Limited) [3].

By using a virtual reality headset for inspections, the movement throughout the 3D model is more natural than using a 2D monitor and allows for a scaled view of the model. When viewing the model on a 2D monitor or even when using the 3D capable monitors, certain 3D elements may obstruct the intended view and would require additional processing of the model to generate a cross-section to view details. Virtual reality allows the user to interact with the model as if they were actually present. Spatial relationships can be easily established and the user is intuitively left with a sense of the model scale. The interface with these models can be used to assist with inspection and subsequent decisions.

Other alternatives to virtual reality headsets require the use of a monitor or projection system positioned to surround the viewer. This system or CAVE (cave automatic virtual environment) uses a series of monitors or screen walls and projectors to give the sense of immersion as shown in Figure 2. The user operates a controller to give the orientation and translation through the model. The benefits are that the CAVE can support multiple participants with one setup. The disadvantages are that often the model doesn't lend itself well to models with complex or irregular surfaces such as topography, curves, protrusions or depressions, angles, etc. The other disadvantage is the high cost of the system.

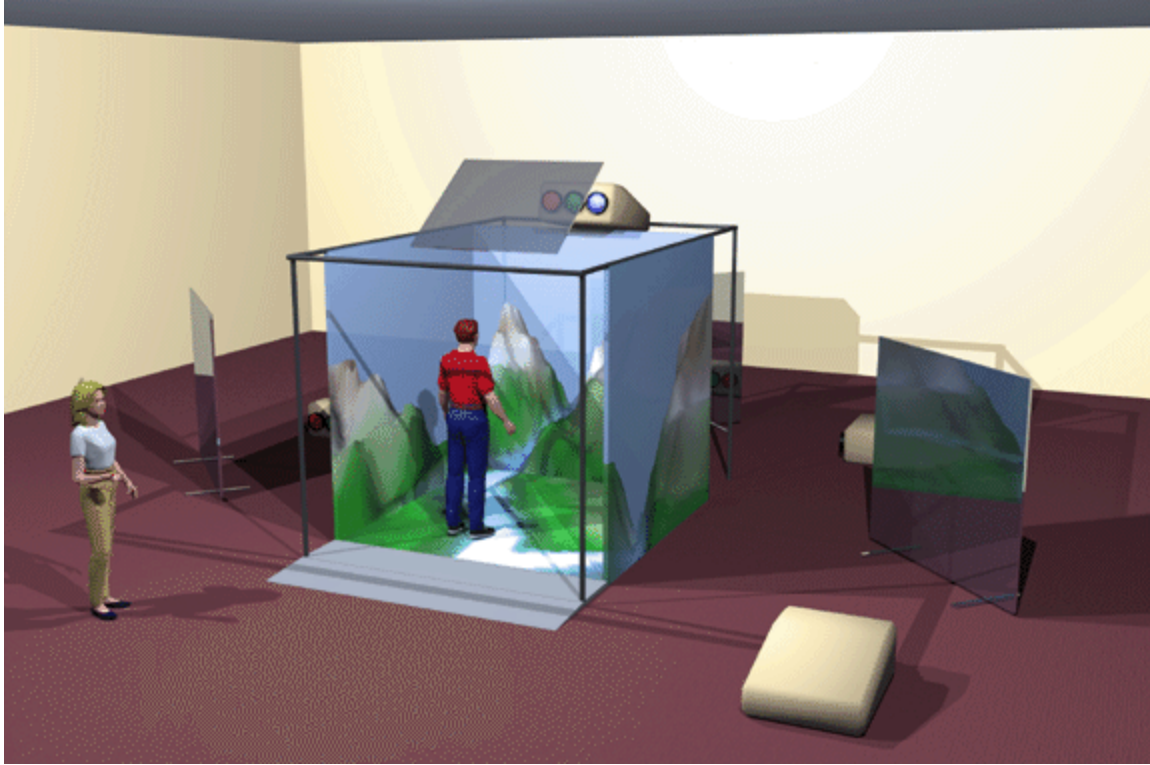


Figure 2: Example of a CAVE System (photo credit courtesy of IU Cave Automatic Virtual Environment)

## Photogrammetric Tools

### Spherical Cameras

The first step of this work was to select a spherical camera. A lower end consumer grade camera was chosen for two reasons: cost and to determine if the lower resolution would be sufficient to produce a 3D model. There is very little documentation regarding selecting and using spherical cameras for photogrammetry so the testing was performed by trial and error. Using a low resolution camera thereby helps determine the lower bounds of equipment requirements.

At the time that this research was conducted there were very few consumer grade spherical cameras to choose from. The camera chosen for testing was the Ricoh Theta m15 (see Figure 3). This camera features two sensors and onboard image synchronization to generate the 360 degree image. The output file is in jpg format with about 6 MP resolution. The camera does not feature full manual support, however it does have shutter priority or ISO priority shooting modes. Due to rapidly increasing availability of virtual reality hardware in early 2016, more affordable and higher quality camera options are now available.



**Figure 3: Ricoh Theta m15 Spherical Camera; note lenses on either side of housing**

Table 1 features a complete list of spherical cameras that were available at the time of writing this report. This list was compiled in part from several websites that summarized spherical camera specifications as well as the different manufacturer's websites [3], [4], [5], [6].

**Table 1: List of Spherical Cameras**

<b>Manufacturer</b>	<b>Model</b>	<b>Resolution (MP)</b>	<b>Number of Sensors</b>	<b>Approximate Cost (2016)</b>
Ricoh	Theta M15	6.3	2	\$210.00
Ricoh	Theta S	14.4	2	\$350.00
Bubl	Bublcam	14.7	4	\$300.00
Sphericam	V2	8.3?	6	\$2,500.00
360Fly	4K	8	1	\$500.00
Kodak	SP360 4K Dual	8	2	\$900.00
Giroptic	360cam	8.3	3	\$500.00
LG	360	16	2	\$200.00

<b>Manufacturer</b>	<b>Model</b>	<b>Resolution (MP)</b>	<b>Number of Sensors</b>	<b>Approximate Cost (2016)</b>
Nokia	OZO	8-4	8	\$45,000.00
GoPro	Omni	31.5	6	\$5,000.00
Samsung	Gear 360	25.9	2	\$350.00
Nikon	KeyMission 360	2-20	2	\$500.00
Orah	4i	11.5	4	\$2,200.00
Luna	360	8?	2	\$300.00
Insta	360	8.4	2	\$550.00
Elmo	QBiC Panorama X	5	4	\$1,380.00
Vuze	VR 3D 360	8-?	8	\$800.00
Facebook	Surround 360 VR	17-4	17	\$30,000.00
NCTech	iris360	32	4	\$2,000.00
NCTech	iSTAR	50	4	\$5,390.00
Panano	Panono	108	36	\$1,500.00
360Heros	Pro10HD Bullet360	72	10	\$1,740.00
Google	Jump	64?	16	\$8,000.00
Jaunt	24R	128	24	\$4,500.00/day
Jaunt	24G	32	24	\$4,500.00/day
Lytro	Immerge	Not applicable	Not applicable	\$250,000.00
VSN	V.360	8	1	\$450.00
Freedom360	GoPro Mount	15.6	6	\$500.00
Headcase	Cinema Quality VR 360	21.7	17	Rental?
Mobius	POV VR 360	?	17	Rental?

<b>Manufacturer</b>	<b>Model</b>	<b>Resolution (MP)</b>	<b>Number of Sensors</b>	<b>Approximate Cost (2016)</b>
Panocam3D	POD 3D 360	8	2x12	\$5,000.00
Panocam3D	HMC 3D 360	24-?	2x9	Rental?

The list provides the manufacturer and model of the camera as well as the still image resolution in megapixels. While the resolution of the camera is very important to the photogrammetric process, resolution alone is not a good indicator of image quality. High resolution images can often be low quality because the actual size of the pixel receptor on the camera sensor is small (called pixel pitch). The number of sensors should also be compared when considering the resolution of a camera and that information is also shown in the table.

In some cases, the actual resolution of the image is not available. Many manufacturers listed only the resolution of individual sensors but did not give the resolution of the final stitched image. If only the number of cameras and individual resolution is known, the resolution is given as X-X meaning the number of cameras and the individual resolution. The typical spherical camera application is intended for video capture and not for still image capturing and photogrammetry. Thus the frame of the video is cropped to current industry standards such as 1080, 2k or 4k formats. In cells where the information is provided followed by a question mark, the information was not able to be verified.

Other features that should be considered are the sensitivity to low light scenes, control over the aperture, shutter speed, ISO and white balance and the actual stitching quality.

The 2016 cost is also shown provides an indication of entry level, consumer grade and professional quality cameras. Some of the cameras shown are not yet available. The Sphericam V2, Orah 4i, Luna 360, Vuze VR 3D 360, and the Panocam3D HMC 3D 360 are scheduled to be released within the next year. Some of the higher end professional cameras used mainly for cinematic productions are available by rental only. These include the Jaunt 24R and 24G, Headcase Cinema Quality VR 360, and Mobius POV VR 360. The Lytro Immerge is a different kind of camera system that utilizes several hundred sensors to capture all light rays within an area. The Panocam3D POD 3D 360 and HMC 3D 360 are stereoscopic 3D spherical cameras and both the Mobius POV VR 360 and Panocam3D HMC 3D 360 are head mounted rigs which attempt to recreate a view from the point of an individual's eyes. Some cameras feature a global shutter which opens each pixel for capturing the light at the same time making the image a simultaneous exposure. This is important for scenes where there may be movement causing a slight angle in the image. Cameras with a global shutter are the Sphericam V2 and Facebook Surround 360 VR.

Several of the listed cameras are actually frames that hold several cameras and then the image(s) or video are postprocessed to generate the spherical image or video. Those cameras are the Kodak SP360 4K Dual, GoPro Omni, 360 Heros, Google Jump, Freedom360 GoPro Mount, and the Headcase Cinema Quality VR 360. The Facebook 360 VR offers the plans to make a

spherical camera from readily available parts. There are also many other do-it-yourself 3D printed frames and plans available but that were not included because of the many variations.

Based on this list, several cameras seem appropriate for further investigation for high quality indoor photogrammetric modeling. These include the GoPro Omni, Panano and NCTech iris360.

As mentioned earlier, one of the first cameras acquired was the Ricoh Theta M15. This project also got a chance to work with a photographer from the public relations office to acquire a GoPro Omni system. At the time of this report, the Omni has not been tested but will be used in future work.



**Figure 4: GoPro Omni System (photo credit courtesy <http://vrscout.com/news/gopro-360-omni-camera-rig-on-sale/>)**

The first test using the Ricoh Theta M15 was performed at a Green Mountain Dam utility room. The dam is located near Silverthorne, CO. The camera was mounted on a tripod and a series of images were captured at different heights and locations throughout the roughly 16 foot square room. The room housed several pumps and related piping. Theoretically, only 3 different locations are required to solve for each pixel location but because of the objects in the room, a total of seven images were collected. The maximum error was refined to just less than one pixel and the model solved using about 5,000 tie points. See Figure 5 for a plan view of the tie points, room outline and camera positions. The basic model geometry was as expected however due to the low image resolution, many of the details in the pumps and pipes were not resolved (see Figure 6).





**Figure 5: Green Mountain Dam utility room plan view**



**Figure 6: Photogrammetric rendering of the interior of the Green Mountain Dam utility room**

## Virtual Reality

Some of the first examples of available virtual reality hardware solutions to encourage interest and development were the Google Cardboard viewer and associated app. The Google Cardboard viewer was introduced originally as a set of plans that allowed the viewer to be built from low cost parts. Eventually, vendors made the viewer available for purchase in either simple, inexpensive cardboard frames or more expensive and sophisticated plastic cases with head straps and Bluetooth controllers.

The Google Cardboard virtual reality system is meant to pair with a compatible smartphone to immerse the viewer in different apps, whether for games, viewing 360 video and images or other applications. A “Cardboard” compatible app is required to be installed on the smartphone and then the smartphone is placed into the Cardboard viewer. The viewer has two lenses to magnify the smartphone screen and a switch on the top of the viewer for selecting settings (see Figure 7).



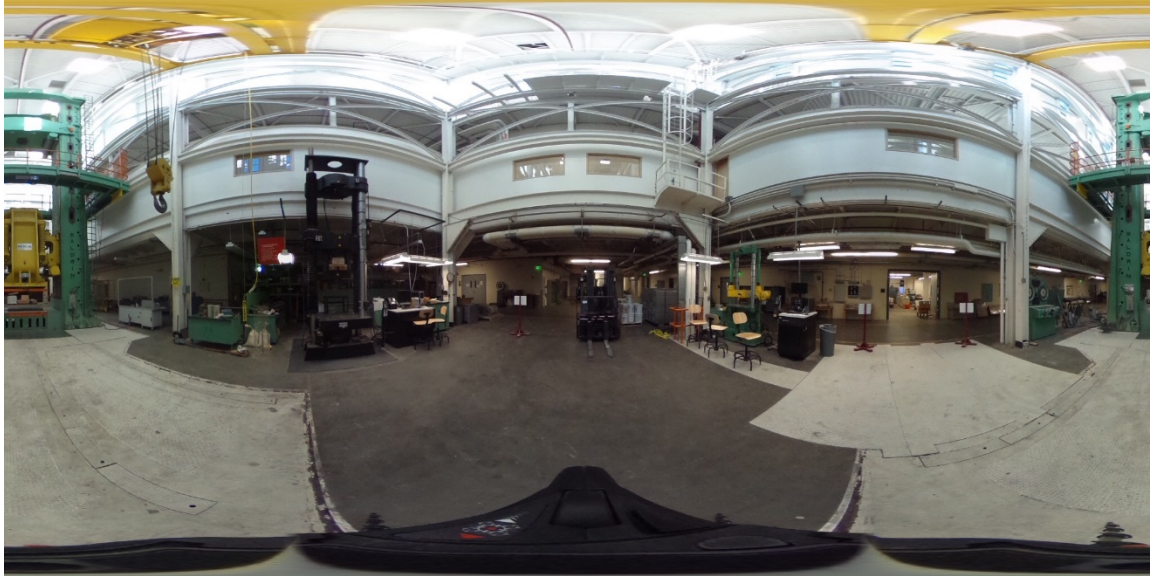
**Figure 7: Google Cardboard version 1 (left) and version 2 (right)**

The Cardboard viewer was initially used to test the usability of virtual reality by taking spherical images and viewing them<sup>1</sup> through the viewer. The first image was taken using the Ricoh Theta M15 in the five million pound universal testing machine bay at the Materials Engineering and Research Laboratory in Denver, CO (see . The picture was saved to the Roundme app for viewing with the Cardboard viewer though other apps may be available depending on the smartphone.

---

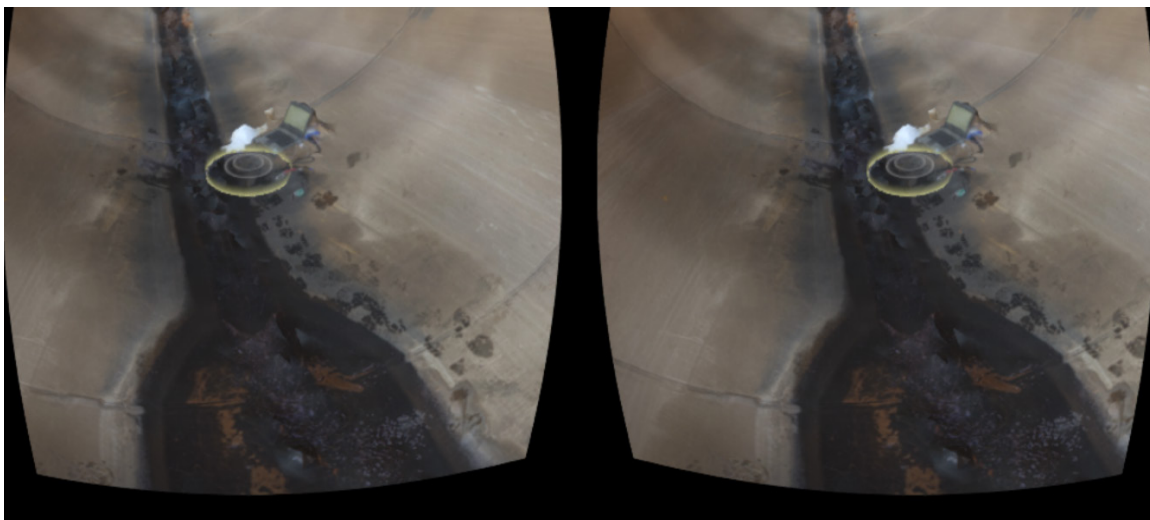
<sup>1</sup> Note that the Cardboard app switch only works with the second version of the viewer.





**Figure 8: Spherical Image Capture of Reclamation testing equipment**

While the Roundme app could convert the spherical camera image to a VR experience, the next step was to find a way to view the photogrammetric 3D models using a VR viewer and be able to execute a “walk-through” of the facility. At this point, only Sketchfab has been tested for hosting 3D models. The 3D model can be exported directly from the photogrammetry software (Agisoft Photoscan Professional 1.2.6) to the Sketchfab website once the mesh has been textured. The model can be viewed and manipulated in 2D using the browser app. To enter the Cardboard environment, the VR button is selected at the bottom of the model viewing window. This launches a fullscreen page for viewing within the Cardboard viewer. The viewer switch is used to navigate through the model. A yellow circle cursor is displayed at the center of the screen for any surface where the position can be advanced (see Figure 9). Note that the view cannot be advanced to any vertical surface.



**Figure 9: VR 3D model of Glen Canyon Unit 2 Penstock (note yellow circle cursor)**

For viewing high resolution models and to enable more features, a computer connected VR viewer is required. There are several models available now and many more in development. The two major VR headsets are the Oculus Rift and the HTC Vive. A good resource to browse nearly all VR headsets is the Virtual Reality Headsets website published by Hypergrid Business. The list is updated occasionally and is very comprehensive [7]. Both headsets are relatively the same in terms of functionality though the Vive offers augmented reality integration that helps the user know where they are in their actual space. Both headsets use dual handheld controllers to interact with the virtual environment (Oculus controllers are expected to be released by the end of 2016). Both headsets also require high end computer hardware especially for the graphics.

The dual handheld controllers would be used to navigate through and interact with the model such as accessing and inspecting inaccessible features and to add comments or markers for areas that need noted on an inspection report. The controllers could also be used to provide measurements such as length, width, area and volume. These features are referred to as annotation options.

The Oculus Rift was acquired for evaluation and testing (see Figure 10). The headset was connected to a custom photogrammetry computer with a liquid cooled 10-core Intel processor, 128 gb DDR4 RAM, 1 TB SSD hard drive and two NVIDIA Geforce GTX 1080 VR ready graphics cards. Getting a model to be viewed on the headset was more challenging than the smartphone/Cardboard solution. There are several ways of viewing 3D models either using a website to host the model or by using a local program. The benefit of having a website hosted model is that a link can be sent to clients to allow them to view the model whether they have a VR headset or not.



**Figure 10: Oculus Rift VR headset**

The VR enabled software solutions include several 3D game creation platforms including Unity, Unreal Engine and Destinations. These programs are not for a novice user and require 3D modeling experience. Iris VR is a software package developed specifically for engineers, architects, and contractors for integration with Revit, Sketchup and other 3D formats such as the ones generated by the photogrammetry software. While the software has not been evaluated in the lab yet, it promises to provide easy navigation and annotation with the VR handheld controllers. While the photogrammetry software (Agisoft PhotoScan Professional) does not support VR functionality at the moment, it was posted to the Feature Requests section of the Agisoft Forum [8].

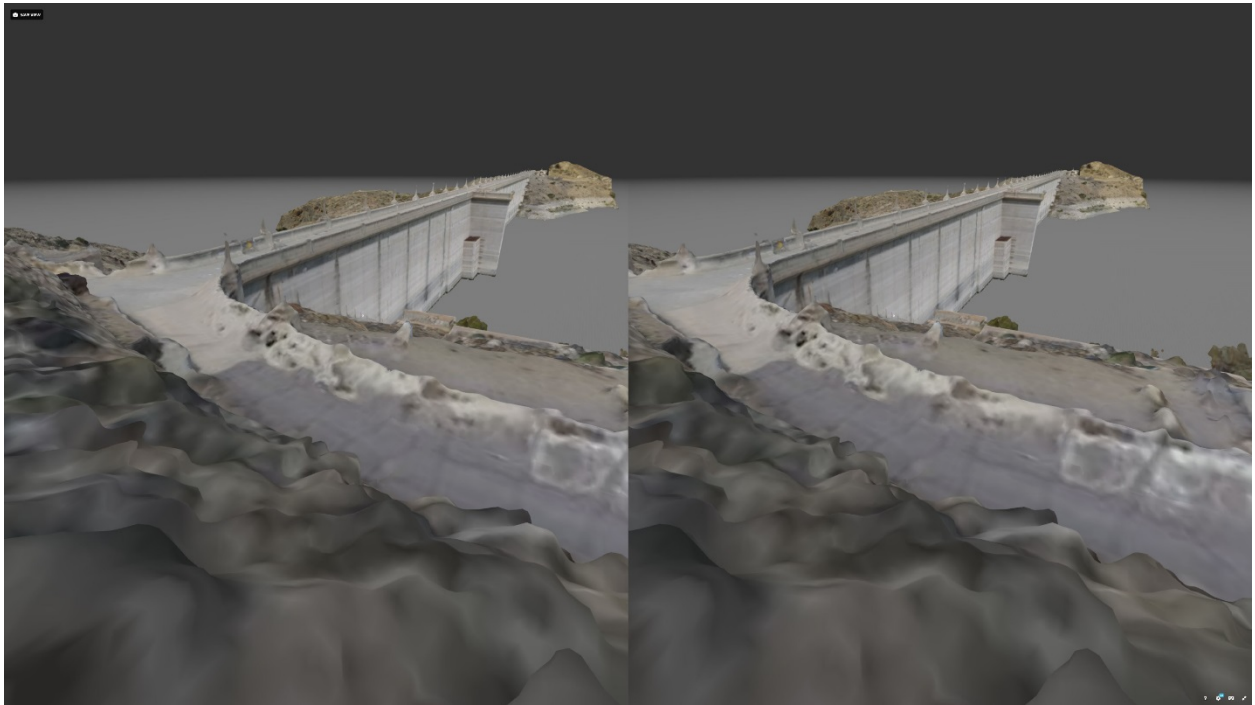
Website offerings for 3D model VR integration include Insite VR and Sketchfab. As mentioned earlier, Sketchfab is the only VR 3D modeling viewing and navigation solution to be tested at this point. This was because the photogrammetry software used at Reclamation has in-program model upload capabilities to this service. The software converts, compresses and uploads the model from within the interface. Sketchfab will send a notification by email once the model is processed. At this point, there is not a standard web browser that allows VR viewing natively, however, there are open-source browsers based on either Google Chrome or Mozilla Firefox that can allow VR browsing: Chromium and Firefox Nightly. Once installed, WebVR must be enabled in the settings. Also, the Oculus Rift setting must be enabled to allow external applications to control the headset. In this case, Chromium build 54.0.2792.0 was used. Once the model was ready for viewing in Sketchfab, the VR button is selected and the model is able to be viewed in the Oculus Rift headset. The user controls rotation through the model using their head and navigation to a new position is done using a controller, selecting a non-vertical surface with an on-screen position marker. The Oculus Rift interface also allows for redefining the scale which allows for better positioning at vertical surfaces.

Currently, four models have been evaluated using this method: Grand Coulee Dam Gate 3 Piers and Approach Apron (see Figure 11); Elephant Butte Dam, Spillway and Powerhouse (Figure 12); Glen Canyon Dam Unit 2 Penstock Transition (Figure 9); and Green Mountain Dam Utility Room (Figure 5). The resolution of the model was downgraded from the photorealistic texture overlaid in the photogrammetry software. The mesh and file sizes are given. The Grand Coulee Dam model featured 475,100 faces and the file size was 46.3 MB, the Elephant Butte Model featured 8 million faces and was 242.7 MB, the Glen Canyon model featured 104,200 faces and was 24.3 MB and the Green Mountain Dam model had 180,000 faces and was 16.9 MB. Overall, the models were realistic and generally easy to navigate. Annotation options such as model marking and measuring were limited but expected to increase as demand for usage increases.





**Figure 11: VR 3D Model of Grand Coulee Dam Gate 3 Pier**



**Figure 12: VR 3D Model of Elephant Butte Dam**

# Conclusions

Using advanced photogrammetric techniques and analysis will help to improve condition assessment of Reclamation facilities. The use of high resolution images from quality spherical cameras will help to improve the quantity of indoor data collection and reduce the time to collect the data. Virtual reality headsets will improve spatial reference, communication and identification of potential trouble areas throughout a facility. The use of VR for condition assessments will increase safety and reduce costs by limiting access to dangerous, inaccessible or confined spaces and by reducing onsite inspection schedules.

The application of spherical cameras at Green Mountain Dam showed a dramatic reduction in data collection time by reducing the amount of setups. Preparing models for VR navigation and manipulation required a significant setup process but as the demand for VR in engineering and construction applications increase, these processes will become streamlined.

More evaluation should occur with respect to spherical cameras, virtual reality and other advanced photogrammetric techniques. This will allow Reclamation to stay current with emerging and evolving technology and assess its uses for Reclamation.

The following list summarizes the results of this study:

- A table of available spherical cameras is provided (see Table 1). The table lists camera manufacturers and models, their resolution and number of sensors and 2016 cost.
- Spherical cameras can be used to capture indoor photogrammetric data more efficiently than traditional frame camera.
- A 3D model was generated from a low-cost, low-resolution spherical camera at Green Mountain Dam.
- Reclamation should invest in a higher resolution spherical camera for high quality photogrammetric 3D modeling; recommendations are given.
- Virtual Reality (VR) headsets provide the ability to intuitively view and navigate through a photogrammetrically generated 3D model.
- Several models were rendered for VR viewing including Grand Coulee Dam Gate 3 Piers and Approach Apron; Elephant Butte Dam, Spillway and Powerhouse; Glen Canyon Dam Unit 2 Penstock Transition; and Green Mountain Dam Utility Room.
- The resolution of the VR model within the VR viewer was downgraded to reduce file size. Future viewers should preserve the native resolution of the model for inspection purposes.
- Other VR rendering softwares should be evaluated.

# References

- [1] M. Klein and C. Lucero, "Photogrammetric Tools for Condition Assessment of Reclamation Structures," Bureau of Reclamation, Denver, 2015.
- [2] D. Semyonov, "Community Forum: Algorithms used in Photoscan," 02 05 2011. [Online]. Available: <http://www.agisoft.com/forum/index.php?topic=89.0>. [Accessed 2016].
- [3] C. A. Cardno, "Virtual and Augmented Reality Resolve Remote Collaboration Issues," *Civil Engineering*, pp. 40-43, September 2016.
- [4] J. M. Oscillada, "List of Consumer 360-Degree Cameras," 05 07 2016. [Online]. Available: <http://www.virtualrealitytimes.com/2016/07/05/consumer-360-degree-cameras-list/>. [Accessed 2016].
- [5] L. Prasuethsut, "Best 360 Cameras," 24 06 2016. [Online]. Available: <http://www.wareable.com/cameras/best-360-degree-cameras>. [Accessed 2016].
- [6] Proteus VR Labs, "360 degree cameras for 360 degrees video or virtual reality experiences," 03 02 2016. [Online]. Available: <https://www.flyvr.com/360-degree-cameras-videos-virtual-reality/>. [Accessed 2016].
- [7] admin, "The Ultimate List of Virtual Reality and 360 Spherical Cameras," 08 06 2016. [Online]. Available: <http://www.viarbox.com/2016/06/08/ultimate-list-virtual-reality-360%CB%9A-spherical-cameras/>. [Accessed 2016].
- [8] editor, "Virtual Reality Headsets," 18 06 2016. [Online]. Available: <http://www.hypergridbusiness.com/faq/best-virtual-reality-headsets/>. [Accessed 2016].
- [9] dmdoc, "Community Forum: VR Support in App," Simple Machines, 17 08 2016. [Online]. Available: <http://www.agisoft.com/forum/index.php?topic=5745.0>. [Accessed 2016].