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USING PHOTOGRAMMETRY TO ESTIMATE TANK WASTE VOLUMES FROM VIDEO

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Abstract: Washington River Protection Solutions contracted with HiLine Engineering & Fabrication, Inc. to use photogrammetry to estimate the volume of simulated waste piles in the video Camera/CAD Modeling System (CCMS) test video and to estimate the volume of waste in tank 241-C-104 from post-retrieval videos. This report meets the contractual requirements of Washington River Protection Solutions (WRPS) Contract # 50464.

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1.0 INTRODUCTION

Washington River Protection Solutions (WRPS) contracted with HiLine Engineering & Fabrication, Inc. to assess the accuracy of photogrammetry tools as compared to video Camera/CAD Modeling System (CCMS) estimates. This test report documents the results of using photogrammetry to estimate the volume of waste in tank 241-C-104 from post-retrieval videos and results using photogrammetry to estimate the volume of waste piles in the CCMS test video.

The test results documented in this report meet the contractual requirements of Washington River Protection Solutions (WRPS) Contract # 50464.

2.0 TEST RESULTS

Test procedures, results and discussion of results developed by HiLine are attached:

- Attachment 1. PHOTOGRAMMETRY FOR COLD TEST FACILITY,
- Attachment 2. PHOTOGRAMMETRY FOR TANK 241-C-104

3.0 CONCLUSIONS

HiLine used industry leading software & methods, but was unable to obtain useful automated photogrammetry results from the CCMS test video. Consequently, volume estimates could not be determined. Several issues and recommended actions were identified to improve future video for photogrammetry, these include:

- Use a fixed zoom lens,
- Remove text overlay,
- Use soft well balanced lighting,
- Use a digital video signal to prevent diagonal interference,
- Increase feature count.

Using the post-retrieval video provided for tank C-104, the photogrammetry software estimated a waste volume of 499 ft³. This estimate is much higher than both preliminary estimates (RPP-CALC-53365, *Waste Volume of Single-Shell Tank 241-C-104 Remaining after Hard Heel Retrieval*) and final CCMS estimates (RPP-CALC-54284, *Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate For Tank 241-C-104*) using the same video.

The photogrammetry approach utilized minimizes, but does not eliminate, the human interaction required to interpret the data & results. While the post-retrieval video for tank C-104 was a better quality video for photogrammetry compared to the CCMS test video, many of the same issues and recommendations apply to improve results.

Key recommendations include:

- Higher resolution images,
- Still frame digital single lens reflex camera (DSLR),
- Soft lighting.

4.0 REFERENCES

RPP-CALC-53365, 2012, *Waste Volume of Single-Shell Tank 241-C-104 Remaining after Hard Heel Retrieval*, Rev. 0, Washington River Protection Solutions, Richland, Washington.

RPP-CALC-54284, 2013, *Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate For Tank 241-C-104*, Rev. 0, Washington River Protection Solutions, Richland, Washington.

Attachment 1

PHOTOGRAMMETRY FOR COLD TEST FACILITY CCMS TEST VIDEO

HILINE ENGINEERING AND FABRICATION

TEST REPORT

PHOTOGRAMMETRY FOR COLD TEST FACILITY
CCMS TEST VIDEO

WRPS, LLC SUBCONTRACT NO. 50464

TR-1212-WRP-209-002, Rev. 0

Approved by: Date: 2-28-13
Troy Stokes, HiLine Lead Engineer

Approved by: Date: 2-28-13
Sherri Brisbin, HiLine QA

1.0 INTRODUCTION

Washington River Protection Solutions (WRPS) contracted with HiLine Engineering & Fabrication, Inc. to perform a feasibility study to assess laser instrument accuracy as compared to known waste volumes and CCMS estimates.

This test report was prepared to document the results of the CCMS effort based on existing video from the Cold Test Facility (CTF).

The test results documented in this report meet the contractual requirements of Washington River Protection Solutions (WRPS) Contract # 50464.

2.0 HISTORY

2.1 Background

WRPS is responsible to clean out single shell waste tanks at Hanford. A tank is considered clean if less than 360 ft³ of waste remains after retrieval efforts conclude.

WRPS utilizes in tank video systems to aide in the operation of retrieval / cleaning equipment and to determine the volume of waste left after retrieval efforts conclude. WRPS analyzes these videos and manually transfers information from the videos to AutoCad to estimate the residual volume of tank waste.

The present WRPS approach results in approximately 20% error, is somewhat subjective, and is reliant upon human interpretations during video processing.

This contract scope explored the cutting edges of photogrammetry processing software with the goal to provide more accurate and faster residual waste volume estimates. An optimum outcome is the creation of a 3D model that can compute the volume of residual waste left in tank C-104, while minimizing any human interpretations.

Automated photogrammetry methods were used to evaluate a CTF Test Video and a post-retrieval video from tank C-104. The following information relates to the CTF Test Video only.

2.2 CTF Video

WRPS arranged known piles of material inside the CTF facility. WRPS then videotaped these piles with a typical "in tank" camera used for tank retrievals / cleaning.

WRPS provided this video to HiLine for photogrammetry purposes on compact disks labeled "CFT2006 disc 1 and disc 2".

3.0 PERSONNEL

The following personnel were involved with this task.

HiLine Engineers: Paul Plummer, Troy Stokes

HiLine QA/QC: Sherri Brisbin, Troy Stokes

Cognitics Inc. Photogrammetry Expert: Kevin Bentley

Personnel qualifications are on file in accordance with the HiLine QA Manual.

4.0 SUMMARY OVERVIEW

A 3D reconstruction based on the CTF video was impossible due to several issues with the video.

The balance of this document describes the process that was performed, the issues encountered, and suggestions to improve the results in the future.

4.1 Photogrammetry Process

The camera used for the CTF video was the RJ Electronics model RCS-2010B. The widest angle field of view for this camera was 46 degrees, based upon available specifications. Unfortunately, the specifications provided by the manufacturer do not indicate the electronic sensor size for the camera, so it was not possible to determine the exact focal length. To allow any analysis, the camera sensor was assumed to be a standard $\frac{1}{4}$ format video sensor, which has a width of 4mm.

The subject video used a variable zoom, which made it impossible to calculate the focal length in frames where the zoom was not at the widest angle. As long as most images are at the widest angle, the bundle adjust can correct the focal length in a subset of the images. Bundle adjust is a processing step that can compensate for incorrect data in some frames.

The focal distance of the lens for each image is required to perform the structure from motion steps necessary to reconstruct the 3D scene from frames. The software requires the focal length in terms of pixel size. The size of the sensor, the field of view, and the width of the image are all utilized to calculate the focal length.

The video was processed through Adobe Premiere and exported one frame per second to high quality JPG images. The creation of JPG images can cause compression artifacts. As an integrity check, several frames were exported as uncompressed PNG images for comparison to the JPG images. No detrimental artifacts were discovered. In addition, the feature detection software was applied to PNG & JPG images, which also verified the same features were detected in all images.

The frames were analyzed for unusable images. The majority of the video had issues that made the frames problematic or even unusable for automatic computer photogrammetry. The best frames were identified as ranges of frames. A custom python script was used to process only the useable images.

Each frame had text overlaid on the screen. The feature detection software allowed the exclusion of certain parts of each image from feature detection. The frames were analyzed to determine which parts of the screen to ignore due to artifacts of the video capture process. The areas ignored were the edges of the image and the text overlaid portions of the frames.

A custom version of the SIFTGPU software was utilized to detect features in each image. This process stored a file along with each frame that contained all of the features detected in the image after filtering out the excluded areas.

After all images were processed for feature detection, images were compared to identify matching features. There were approximately 5000 images available for feature detection. Matching 5000 images against each image in the set would have required 25 million comparisons. On a modern personal computer, even with multithreading and graphics card acceleration, this process would take many weeks.

Fortunately, the video frames can be processed sequentially, since the camera is moving at a mostly steady rate. However, removal of frames with image quality issues created gaps in the motion of the video. The feature matching software was modified to process images sequentially plus consider the interval. Each image was compared to the neighboring 10 images in the sequence, and also compared to every 20th images in the set. These processing steps reduced the 25 million possible comparisons to only 1.3 million.

The final step utilized the bundle adjust algorithm. This algorithm attempts to find a least squares solution to a system of equations. Each image had a camera position that was represented as an unknown in the equation. The equation used the RANSAC algorithm to find the solution for each image with the greatest number of inliers and then fit the curve for the inliers only.

Unfortunately, using the video data from the CTF videos, the software was not able to converge on a solution. The 3D scene could not be reconstructed with this video. This was very unusual for automatic photogrammetry using the SIFT algorithm for feature detection. There are a number of reasons for this problem, which are described later in this document.

5.0 PHOTOGRAMMETRY DETAILS

Note: In the screen captures in this document, the colored arrows and lines on the image represent the Scale-Invariant Feature Transform (SIFT) features, which are a crucial part of the photogrammetry process. SIFT features represent parts of the image that can be matched up with similar features on other images. The direction and size of the arrows are visual indicators of the dominant descriptor in the feature, and are used only to visualize the data.

This section describes the major issues encountered during the processing of the CTF Video.

5.1 Variable Zoom

Typically when processing images for photogrammetry, the video comes from a still camera that records the focal length in the EXIF data for each image. The photogrammetry software reads this data and uses it to establish part of the camera pose matrix. This information is crucial to solve the 4x4 matrix that represents the camera model for each image. Some video sources, such as those provided by unmanned aerial vehicles, encode the focal length with each frame of video.

In this video data set, there was no way to automatically determine the focal length of the images. The focal length had to be estimated based on the camera specifications available, assuming the widest angle zoom.

Each frame that had a zoom factor was less likely to contribute to the 3D reconstruction because the software had to solve the focal length as well as all of the other parameters of the camera model. In the steps performed, the bundle adjust step moved the camera forward or backward to compensate for the zoom factor. This allowed the software to compensate somewhat for the variable zoom. Zoomed video with unknown focal length was detrimental to automated photogrammetry.

For future video, use of a fixed zoom for a video sequence is preferred. If a zoom is used it should be used for an entire section of video and the video should be identified as being shot at a specific zoom factor. Use of a camera with precise sensor specifications (such as the GE camera used in the C-104 data set) available is greatly preferred.

5.2 Overlay

For the purpose of automatic photogrammetry, the text overlay was very problematic. The feature detection software detected the text as features, and matched the text features against every other frame.

The end result was that the software reconstructed the video overlay, and ignored the rest of the scene as outliers. As seen in Figure 1, a large number of features were detected in the text. This cannot be corrected by 'censoring' that part of the image because SIFT features are detected around the edges of the censored area.

To overcome this problem, Cognitics modified the feature detection to ignore features found in the area of the screen where the text appears. This worked well to avoid erroneous features, but further reduced the overall amount of information that could be extracted from each frame. To support automatic processing, the video overlay should be turned off.

Figure 1 - Features Detected with Video Overlay

5.3 Lighting & Shadows

Many frames in the video were characterized by a bright hot spot in the center of the screen, and dark borders around it, such as is shown in Figure 2.

This contrast created strong shadows which were recognized as features. Shadows as features are a problem because they are not fixed features. They contribute to noise, and confuse the 3D reconstruction effort.

The dark areas are not usable for feature detection, and the extreme brightness in the center tended to wash out detail, reducing the feature count further. Soft and well balanced lighting is greatly preferred.

Figure 2 - Lack of Features outside of the spotlight

5.4 Diagonal Interference

Many of the frames in the video had a strong diagonal noise pattern across the screen. This presented a similar problem as the video overlay.

The feature detection software identified the noise pattern as a set of features. Because many frames have similar interference patterns, this caused the feature matching software to see more patterns in the noise than it did in the image. Even in frames where the noise is not very noticeable visibly, it was still detected by the feature detection process.

Most of the video in this dataset was unusable due to this problem.

Use of a digital video signal, or possibly a shorter or better shielded cable may prevent this problem in the future.

Figure 3 - Features detected in noise

5.5 Feature Count

A typical 500x500 image has around 2000 features identifiable.

Figure 4 is a histogram showing the number of features extracted using the images that were not excluded due to noise or other issues mentioned above.

The vast majority of the images had less than 100 features for a 720x480 image. The more SIFT features that can be matched across images, the more points that can be extracted into the final result.

The small number of features found in this data set are the result of poor lighting conditions, a relatively homogeneous image (e.g. the smooth light colored sand piles), and a video camera that lacks sharpness.

(Initial tests of the C-104 dataset show a much higher feature count due to better lighting and a sharper image.)

Figure 4 - Features per image

6.0 CONCLUSION

Automated photogrammetry results are not available from this CTF video. There are no findings to compare with the WRPS "known volume". Electronic files available were provided to WRPS with this report.

If the issues identified in this document are eliminated in future video, automated photogrammetry will have a much better ability to determine the results.

Attachment 2

PHOTOGRAMMETRY FOR TANK 241-C-104 VIDEO

HILINE ENGINEERING AND FABRICATION

TEST REPORT

PHOTOGRAMMETRY FOR TANK 241-C-104 VIDEO

WRPS, LLC SUBCONTRACT NO. 50464

TR-1212-WRP-209-003, Rev. 0

Approved by: Date: 2-28-13
Troy Stokes, HiLine Lead Engineer

Approved by: Date: 2-28-13
Sherri Brisbin, HiLine QA

1.0 INTRODUCTION

Washington River Protection Solutions (WRPS) has contracted with HiLine Engineering & Fabrication, Inc. to determine the volume of residual waste in tank C-104 using modern photogrammetry methods & software.

This report has been prepared to document the results obtained from the existing video from the C-104 tank.

The results documented in this report meet the contractual requirements of Washington River Protection Solutions (WRPS) Contract # 50464.

2.0 HISTORY

2.1 Background

WRPS is responsible to clean out single shell waste tanks at Hanford. A tank is considered clean if less than 360 ft³ of waste remains after retrieval efforts conclude.

WRPS utilizes in tank video systems to aide in the operation of retrieval / cleaning equipment and to determine the volume of waste left after retrieval efforts conclude. WRPS analyzes these videos and manually transfers information from the videos to AutoCad to estimate the residual volume of tank waste.

The present WRPS approach results in approximately 20% error, is somewhat subjective, and is reliant upon human interpretations during video processing.

This contract scope explored the cutting edges of photogrammetry processing software with the goal to provide more accurate and faster residual waste volume estimates. An optimum outcome is the creation of a 3D model that can compute the volume of residual waste left in tank C-104, while minimizing any human interpretations.

Automated photogrammetry methods were used to evaluate a CTF Test Video and a post-retrieval video from tank C-104. The following information relates to the C-104 Video only.

WRPS provided video from tank C-104 on compact disk.

3.0 PERSONNEL

The following personnel were involved with this task.

HiLine Engineers: Paul Plummer, Troy Stokes

HiLine QA/QC: Sherri Brisbin, Troy Stokes

Cognitics Inc. Photogrammetry Expert: Kevin Bentley

Personnel qualifications are on file in accordance with the HiLine QA Manual.

4.0 SUMMARY

This document describes the research effort performed using the video from the C104 Tank.

Although the video was not ideal for photogrammetry, it provided enough resolution and diversity to reconstruct a 3D model of the inside of the tank.

The video was processed into a point cloud and then the point cloud was reconstructed into a surface.

The volume of material remaining inside the tank was calculated at 499 ft³.

5.0 PHOTOGRAMMETRY DETAILS

5.1 Focal Length

The focal distance of the lens was required from each image to perform the structure from motion steps to reconstruct the 3D scene from frames. The software requires the focal length in terms of pixel size. Therefore the size of the sensor, the field of view, and the width of the image were all needed to calculate the focal length.

The camera used was the GE model PTZ70. This utilizes a ¼ sized sensor. This size sensor has a 4 mm diagonal size, and a width of 3.2mm. At 1 meter the image height was 637mm and the height was 849mm. The images stored on the DVD are 720 x 480. Using the triangle formed by the image size of 849mm wide at 1000mm distance, the focal length was calculated at 3.77mm or 848 pixels.

The subject video used a variable zoom, which made it impossible to calculate the focal length in frames where the zoom was not at the widest angle. As long as most images are at the widest angle, the bundle adjust can correct the focal length in a subset of the images.

The camera positions calculated (for images where the camera was zoomed) will appear at a different location than where the true camera location to compensate for the changed field of view.

Figure 1 - Focal Length Calculation

All values are measured "in air" and are approximate with slight variations based on NTSC or PAL format. Multiply values by 0.75 for underwater FOV or target size. Magnification increases x1.33 for underwater use.

[†]Screen magnification calculated assuming 6.4" diagonal LCD screen.

Figure 2 - Camera specifications used to determine the focal depth

5.2 Export & Analyze Images

The video was processed through Adobe Premiere and exported one frame per second to high quality JPG images.

The creation of JPG images can cause compression artifacts. As an integrity check, several frames were exported as uncompressed PNG images for comparison to the JPG images. No detrimental artifacts were discovered. In addition, the feature detection software was applied to PNG & JPG images, which also verified the same features were detected in all images.

The frames were analyzed for unusable images. Most of the video frames were evenly lit and sharp, making them usable. There was a persistent amount of noise through much of the video, but it was random enough to not disrupt the automated process.

The video frames were manually reviewed to select only the best quality frames from select sequences whenever $\frac{1}{4}$ of the image changed. This manual process allowed selective elimination of noisy frames, as well as frames with bad lighting. After manual review, 773 of the highest quality images representing all areas of the tank were selected.

Each frame had text overlaid on the screen. The feature detection software was configured to exclude certain parts of each image from feature detection. Portions ignored included text overlays & edges of the images, which had artifacts from the video capture process.

Figure 3 - Sections of the image with overlaid text and graphics were filtered from the results

5.3 Feature Detection

A customized version of SIFTGPU software detected features in each image. This process stored a file associated with each frame that contained all of the features detected in the image after filtering out the excluded areas.

Frames from this video had an average of 775 features even after filtering out the overlay areas. This provided a good basis for the structure from motion process.

Each frame was processed to identify similar features across each image.

A bundle adjust process was used to determine the relative camera pose for each image. This process was an iterative curve fitting process that adjusted the camera pose to reduce the error between images. The bundle adjust process converged with a model containing 22,362 3D points.

In the process, features from 12 images were discarded because a pose from the camera could not be determined. These images were all from a section of the tank where a very bright light was dominate in the image. Due to the drastically different lighting, the features from these 12 images could not be automatically correlated with the other 761 images.

Figure 4 - Extracted point cloud with camera pose

5.4 Conversion to Model

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The tank was modeled with a mathematical function based on the blueprints provided for tank C-104. This model was used to fit the extracted points to real world coordinates.

When processing 3D reconstruction, the coordinate system depends on the initial pair of images used to build the model. This means there is no fixed concept of up, and the units depend on the focal length that the bundle adjust process determined.

By building a reference model and running a curve fitting algorithm against the extracted point cloud, the point cloud was rotated and scaled to real world coordinates.

Note: The unit of measure was “feet”.

Figure 5 - Rendered 3D model used for reference

5.5 Surface Reconstruction

A surface reconstruction process was used to create a surface from the point cloud using the ball pivoting algorithm¹.

The surface is necessary for calculation of volume in the tank. The reconstructed surface only includes parts of the tank where recognizable features were found. Flat, homogeneous parts of the tank appear as empty space due to the lack of features in that part of the image.

Figure 6 - Reconstructed surface

¹ The ball pivoting algorithm is described in the paper "The Ball-Pivoting Algorithm for Surface Reconstruction"
http://www.research.ibm.com/vistechnology/pdf/bpa_tvcg.pdf

5.6 Determination of Volume

To calculate volume, the reconstructed surface was merged with the reference model of the tank. That allowed calculation of the volume between the empty tank and the reconstructed surface.

The actual volume computation was performed as three separate Riemann sums (the pan, corner, and wall). An epsilon value drives the sampling density. This epsilon value was used to compute appropriate delta values for each dimension/angle so as to create a more uniform sampling. Sampling was done by casting a ray in a particular direction and choosing the closest intersection point along the ray as the sample. If there was no intersection or the intersection occurs outside the tank, then it was ignored since there was no proper volume contribution.

The pan volume was computed in cylindrical coordinates as a series of disks. Each disk was positioned some epsilon value apart starting at the center and emitting outwards to the beginning of the dish component.

Each disk was then sampled so that the arc distance between sample points matches the epsilon value.

For each sampled point, the contributing volume was calculated as follows:

$$v = (z - z_{\text{tank}}) \cdot d\theta \cdot \left(\left(r + \frac{e}{2} \right)^2 - \left(r - \frac{e}{2} \right)^2 \right)$$

This volume assumed that the small sample volume was a delta volume in cylindrical coordinates with the sample point at the center of the top of the volume, and the expected value at the center of the bottom of the volume. $\left(\frac{e}{r}\right)$ in this case was used as $d\theta$. This was so that the arc length was sampled at the same epsilon value to get a more uniform sampling of the scene.

The corner volume was computed in spherical coordinates. The scene was sliced about the center axis and the contribution between each slice was measured. Each slice was broken up into smaller components and sampled along the curve of the dish. Each point was sampled by casting a ray from the localized origin of the corner's curve outwards towards the corner.

Since these sampling volumes were in spherical coordinates, the following equation was used for each sample volume:

$$v = d\phi \cdot d\theta \cdot \cos\theta \cdot \frac{r_{\text{tank}}^3 - r^3}{3}$$

$\frac{e}{33.5}$ was used as $d\theta$ to match the sampling density of the pan and $\frac{e}{4}$ was used for the $d\phi$ value to match the sampling density along the corner arc.

The wall volume was computed in cylindrical coordinates as a series of disks. Each disk was positioned some epsilon value apart moving upward along the z axis. Each point was sampled by casting a ray outwards from the center of the tank (towards the walls) from some point several feet away from the wall. Each point then contributed a small volume equal to:

$$v = e \cdot d\theta \cdot \frac{37.5^2 - r^2}{2}$$

$\frac{e}{r}$ was used as $d\theta$ to allow for a uniform point sampling. (37.5 ft is the known radius of the tank.)

Each contribution was summed to compute the total overall volume.

Figure 7 - Reconstructed surface merged with the reference model

Figure 8 - Reconstructed surface used for volume calculations

5.7 Results

Using the techniques described above, the volume of the material in the tank was calculated at 499 ft³.

The approximate areas were measured as below.

Wall: 570 ft²
Corner: 11 ft²
Bottom: 665 ft²

The materials detected were spread in a thin layer across a large area. The thickness of this layer was the least accurate measurement in the process because of the relatively stationary camera position.

The distance between the camera plane and a feature is inversely proportional to the disparity of the feature between two images taken at different angles².

Based on a resolution of 720 pixels wide, and using the field of view for the camera we calculated that at a depth of 10 meters (393.7 inches) we had a pixel width of 0.446 inches. A disparity of 0.446 inches would represent a depth of 2.24 inches.

Thus for a feature 10 meters distance from the camera, the depth cannot be accurately measured with greater accuracy than one pixel or 2.24 inches.

Because the accuracy is dependent on the position of each feature relative to the camera position for each image that contributed to the feature, there was not a single accuracy value that expressed the confidence in the data.

Because the layer of materials detected is so thin relative to the area, this could dramatically affect the volume calculation in either direction.

5.8 Recommendations

As mentioned above, an image with a resolution of 720 x 480 will have a pixel size of about 1/2 inch at 10 meters distance. When two features are matched across multiple images, the potential error increases by this size for each image processed. This error can accumulate quickly, so higher resolution images are very important.

A single frame image can be shot with much higher resolution and a longer exposure than is possible with a video camera. If possible, future photogrammetry should use a remotely controlled digital single lens reflex (DSLR) camera with a vibration reduction lens. This will provide a much sharper image without the noise of a video camera.

Higher resolution images provide many more features with a higher accuracy. In order to get better results, it is recommended to photograph a tank using a still image camera with soft lighting (few or no shadows).

The accuracy of high quality still images from a DSLR camera can be demonstrated by repeating the "CTF reference standard test" and calculating the volume of that reference. Continued work would provide a known comparison of volume in a controlled environment to compare against our software and methods.

² This statement assumes an identical camera model for both images. The variable zoom used in the video means there is not an identical camera model for all images. This adds some uncertainty to the accuracy of the data because to determine the actual precision limits would require the camera model for each point to determine the precise relationship between depth and disparity.

6.0 COMPARISON OF RESULTS

6.1 Prior Volumetric Results

WRPS provided the following summary level information to include in this report. HiLine cannot and does not attest to the accuracy or methods employed by WRPS to generate this prior information.

WRPS reviewed the C-104 video using their CCMS methods. The results are in the following reports, summarized below.

RPP-CALC-53365, 2012, *Waste Volume of Single-Shell Tank 241-C-104 Remaining after Hard Heel Removal.*

Waste in tank bottom = 158.8 ft³ (based on volume displacement measurement)
 Waste on Stiffener Rings and Walls = 32.1 ft³
 Total = 190.9 ft³

RPP-CALC-54284, 2013, *Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate For Tank 241-C-104.*

Table 3-1. Tank 241-C-104 Total Waste Volume and Component Waste Volumes.

Component	Waste volume			95% UCL ¹ (ft ³)
	m ³	gal	ft ³	
In the bottom (dish) of the tank (solids and liquids)	5.392	1,425	190.4	228
Waste in tank equipment ²	0	0	0	0
On the stiffener ring and tank walls ³	0.753	199	26.6	26.6
Total ⁴	6.145	1,624	217	255

Notes:

1 ft³ = 7.481 gal, 1 m³ = 264.2 gal, UCL = upper confidence limit

¹ Per RPP-23403, *Single-Shell Tank Component Closure Data Quality Objectives*, the estimated CCMS error is calculated using: Volume at 95% upper confidence level = 1.195 * CCMS reading + 0.27 ft³

² Negligible compared to other waste components.

³ The estimated volume for waste on the stiffener ring and on the tank wall is the upper bounding estimate.

⁴ Total may not equal sum of individual volumes because of rounding.

6.2 Discussion of Error

Normally, an average error can be obtained by comparing the curve fit of a known geometry to the photogrammetry points, thereby creating a range of uncertainty for the volume.

In this case, the 3D points were fit to a model of an empty tank. The empty portions of the actual tank are smooth surfaces that were undetectable by the feature extraction process and did not result in many features. Therefore, the average error calculated during the fit was meaningless as a measurement of error, and was only useful as a relative variable that was minimized during the process.

Due to the large areas relative to the volume, it was apparent that the thickness of the material was a very important factor in the total volume measurement. Unfortunately, due to the relatively stationary position of the camera, there are limits that dramatically reduce the accuracy of the thickness measurement.

Photogrammetry is limited by the pixel size of the images and the average distance of the camera to features. This provides an upper limit on the possible accuracy.

The following analysis looks at the pixel geometry and how the distance of the camera to a feature impacts the distance calculation.

In this dataset, a best case was where the vertical separation between two camera positions is 10'. There was an average horizontal distance from the camera to the wall of 37.5 feet. At that range, the vertical size of a pixel is 0.8 inch. Without a detailed characteristic of the subpixel accuracy and the impact of compression on the pixels, it is not possible to determine exactly how accurate the subpixel measurement.

In the best case, with 8 bits of color depth, there would be 256 subpixels assuming an ideal camera sensor with no compression or noise. In the worst case, there would be 1 pixel, or 0 subpixels.

A measurement that is created from two overlapping pixels is limited in its integrity by the geometry of the pixels.

The diagram depicts two pixels projected outwards from cameras separated a distance L such that the pixel diverges at an angle of 2θ overlap in an area around the measurement distance D . The closest point at which the pixels overlap and the further point is described as δ in the above diagram.

By rearranging δ in terms of single angle tangent functions:

$$\delta = \frac{\tan\phi \tan\theta}{\tan^2\phi - \tan^2\theta} (1 + \tan^2\phi)$$

For two cameras separated by a distance of 10' measuring a point at the edge of the tank a distance 37.5' away, and pixel divergence of 0.05° the δ would be 6.146' and thus the tolerance is 8% of the distance from the camera to the feature.

At a range of 37.5', with a best case separation of 10' between camera images and with an ideal subpixel with 256 discrete measurements, that results in an uncertainty of depth at $\frac{6.146'}{256} = 0.288"$. With a camera separation of only 5', the uncertainty doubles. Similarly, if there are only 128 discrete subpixel measurements the uncertainty doubles.

A difference of 0.288" in thickness over an area of 570 feet² results in a difference of 14 feet³ in volume. This is the best case uncertainty based on the limits of geometry.

Most of the image positions are not separated by 10' of vertical distance, and the camera is almost certainly not capable of 256 subpixel measurements, especially when considering compression. By assuming an average vertical separation of 5' and 64 discrete subpixel measurements, that leads to an uncertainty of 2.3" of depth, which results in a difference of 109 feet³ in volume.

Because the reconstructed model is built with N-view images (meaning N images contribute to each point's position determination), there is no way to calculate the precise uncertainty of the model. The above analysis indicates that due to the large area of the material detected relative to the volume, there can easily be errors of over 100 ft³ in the 499 ft³ computed within this report.

HiLine was not contracted to review the details of prior CCMS efforts, and is therefore technically unable to compare and/or contrast the merits of the two independently prepared reports.

However, the issues encountered during this method must certainly have been encountered by prior work. Our issues are defined by mathematics, pixel sizes, and positional limitations of the video provided. It is highly likely the variance of findings is related to the human interaction of the prior reporting, combined with the potential errors in depth discussed in this report derived from equipment limitations (which would affect both reports).

7.0 CONCLUSION

HiLine has completed photogrammetry on the C-104 video using industry leading software & methods to determine the residual waste volume in tank C-104. The approach utilized minimizes, but does not eliminate, the human interaction required to interpret the data & results.

Mathematics & automated processes drove the technical findings (of this report) to the limitation of the video available for review.

A higher quality video / still camera combined with intentionally planned effort (location of camera & lighting) would yield better technical conclusions based primarily in computational math without significant human interpretation.

The electronic files generated during this process were electronically submitted to WRPS with this report.

WRPS should consider optimizing future photogrammetry data collection & equipment to achieve better results based upon the several findings & discussions contained within this report.