Demonstration of Quantitative Waste Volume Determination Technique for Hanford Waste Tank Closure − 11139

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ABSTRACT

The Hanford Site is currently in the process of an extensive effort to empty and close its radioactive single-shell and double-shell waste storage tanks. Before this can be accomplished, it is necessary to know how much residual material is left in a given waste tank and the uncertainty with which that volume is known.

The Institute for Clean Energy Technology (ICET) at Mississippi State University is currently developing a quantitative in-tank imaging system based on Fourier Transform Profilometry, FTP. FTP is a non-contact, 3-D shape measurement technique that can be used with objects of arbitrary shape and whose result is independent of chemical composition. By projecting a fringe pattern onto a target surface and observing its deformation due to surface irregularities from a different view angle, FTP is capable of determining the height (depth) distribution (and hence volume distribution) of the target surface, thus reproducing the profile of the target accurately under a wide variety of conditions. Hence FTP has the potential to be utilized for quantitative determination of residual wastes within Hanford waste tanks.

As part of efforts to develop, characterize, and demonstrate a quantitative imaging system capable of accurate and precise determinations of residual waste volumes remaining in the Hanford tanks, the inherent instrumental volume determination uncertainty has been reduced by replacing the color block camera that had previously used with a monochrome FireWire camera. Reliable volume determinations under a wide variety of lighting conditions indicate that image reconstruction distortions can occur at high illuminations; however, small variations in background illumination will not degrade the fringe pattern image. The method was also found to be insensitive to variations in optical zoom. Furthermore, we report the demonstration of our prototype FTP system in the ICET highbay. The prototype FTP optical instrumentation arm is mounted on a manipulator system that enables precise pan and tilt motion under computer control. The FTP system is mounted above the ICET floor at elevation and records the volumes of a variety of large targets positioned at selected locations. The targets consist of both targets with simple geometry and non-descript targets. The volumes of both types of targets have been independently determined by traditional means. This effort demonstrates the ability of FTP to accurately and precisely determine the volumes of targets of interest under simulated Hanford waste tank conditions.

INTRODUCTION

As part of an on-going, nation-wide effort to environmentally remediate sites where radioactive materials have been processed for the U.S. government, the U.S. Department of Energy (DOE) is engaged in efforts to retrieve wastes stored in tanks at a variety of DOE sites, including Hanford, Oak Ridge, and Savannah River. Because of the volume of wastes involved, the tank closure effort at the Hanford site is the most extensive and involves both its single-shell tanks (SSTs) and double-shell tanks (DSTs) [1-7].

Before a waste tank can be closed, it is necessary to know how much residual material is left in a given waste tank and the chemical makeup of the residue. Mississippi State University's Institute of Clean Energy Technology (ICET) is engaged in efforts to develop, fabricate, and deploy inspection tools for the Hanford waste tanks that will (i) be remotely operable; (ii) provide quantitative information on the amount of wastes remaining; and (iii) provide information on the spatial distribution of chemical and radioactive species of interest. A collaborative arrangement has been established with the Hanford Site to develop probe-based inspection systems for deployment in the waste tanks.

ICET's inspection approach is to independently and quantitatively estimate the amount of residual waste by using Fourier-transform profilometry (FTP). ICET has previously demonstrated that its FTP system can quantitatively estimate the volume and depth of removed and residual material to high accuracy. FTP was developed by ICET for inspection of an off-line Joule-heated melter at the West Valley Demonstration Project [8]. A submersible version of the ICET FTP system has been deployed in the Oak Ridge Research Reactor pool to characterize aluminum pit corrosion [9]. To date, the ICET FTP system has obtained preliminary results utilizing conditions appropriate for the Hanford waste tanks [10-16].

FOURIER TRANSFORM PROFILOMETRY METHOD

Fourier transform profilometry (FTP) is a non-contact, 3-D shape measurement technique [17-19]. A fringe pattern is projected onto the target surface. If that surface is not flat, the fringe pattern, when observed from a different angle, is distorted due to the undulations of the surface. By analyzing the distortion of the fringe pattern, FTP is capable of determining the height (depth) distribution of the target surface, thus reproducing the profile of the target accurately. If changes are made to the surface and if both before- and after-change images of the surface are acquired under the same conditions, the changes can be determined quantitatively by comparing the two images. The principle of FTP is illustrated in Fig. 1.

In Fig. 1, the photo image presents a cone placed on a flat surface with a fringe pattern (repeating fringe lines) projected onto its surface. In this illustration, the cone is the target to be determined. The flat surface is called the "reference plane." Before the target image (with a certain fringe pattern projected) is acquired, a reference image is also acquired. The reference image shows the reference plane with the same fringe pattern projected onto it. It is important to make sure that during the acquisition of both images, the settings of projector, camera, and fringe pattern remain the same. As observed in the target image in Fig. 1, the fringe lines projected onto the cone are distorted. These distortions are caused by surface irregularities and contain height information for the target surface with regard to the reference plane. With the distortions properly interpreted, height information can be revealed.

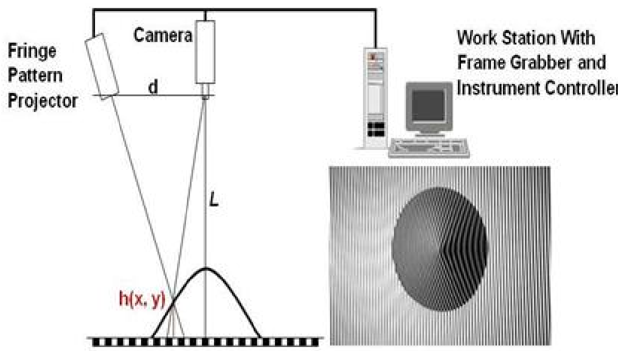

Figure 1. Diagram illustrating the principle of Fourier-transform profilometry.

In FTP, a Fourier transform is first applied to both reference and target images. Then a region of interest in the transformed spectral image, which usually consists of one complete spectrum of the image being transformed, is selected. Inverse Fourier transforms are then applied to the selected spectral region of both images, to extract the phase information. Thereafter, there are two phase images (reference and target) available for further processing. By subtracting the reference phase image from the target phase image, a difference phase image is generated. Since phase information describes how fringe lines are spaced in an image, this difference phase image describes how the spacing of fringe lines of the target image varies from that of the reference image. Therefore, the difference phase image is directly related to the height distribution of the target surface, which caused the difference in fringe line spacing. As derived by Takeda and Mutoh [18], the height distribution of the target surface is easily calculated by using Eq. (1).

$$h(x,y) = \frac{L_0 \Delta\Phi(x,y)}{\Delta\Phi(x,y) - 2\pi d f_0} \qquad \text{Eq. (1)}$$

where $\Delta\Phi$(x, y) gives the phase modulation due to the object-height elevation, *h(x, y)*; L_0 is the distance from the camera aperture to the reference plane; *d* is the distance between apertures of the projector and of the camera; and f_0 is the fundamental frequency of the observed fringe pattern on the reference plane (in lines/cm).

The resolution of FTP measurements is defined as the height (depth) that a single pixel in an acquired image can resolve. It is denoted as Δh_p, and can be obtained from Eqs. (2) and (3):

$$\Delta h_p = \frac{L_0 \Delta\Phi_p}{[\Delta\Phi_p - 2\pi d f_0]} \qquad \text{Eq. (2)}$$

Where

$$\Delta\Phi_p = \frac{2\pi n_{line}}{X_{pixel}} \qquad \text{Eq. (3)}$$

and $\Delta\Phi_p$ stands for the phase shift that a single pixel in the acquired image is able to resolve, n_{line} is the total number of repeating fringe lines in the image, and X_{pixel} is the horizontal image dimension (in pixels). Obviously, the L_0 and d parameters, the density of fringe lines, the dimension of the acquired image, the focal length (F.L.) of the camera lens, and the projector's projected field angle all affect the resolution of FTP measurements.

Fourier transform profilometry is fast, efficient, and inexpensive in comparison with other commonly used profilometry techniques, such as laser profiling methods. FTP provides an ideal quantitative means of determining the volume of residual material remaining in waste tanks.

CHARACTERIZATION AND OPTIMIZATION STUDY

Because Hanford uses a very similar camera in their waste tank retrieval efforts, the initial FTP development efforts utilized a Sony FCB-EX78B color block camera and were able to obtain FTP volume determinations with small errors [10-16]. As a result of camera stability studies, we determined that the Sony 78 B has a rather long warm-up time (30-45 minutes) and even then significant intensity fluctuations [15, 16]. The Sony FCB-EX78B block camera is controlled by a computer via an RS-232 interface using Sony VISCA® control protocol. The digital image acquired by the block camera is converted to an analog signal for transmission to the image acquisition computer, where the image is converted from analog back into digital format for storage. The intensity fluctuations have been attributed to fluctuations associated with the analog-to-digital conversion process. Because these intensity differences are related to the FTP phase changes and hence to FTP height (volume) determinations, it is desirable to utilize a camera that has a short warm-up time and that can transfer the image to the image acquisition computer directly in digital format. Cameras that communicate with the image acquisition computer via IEEE 1394 format do transfer the images in digital format. IEEE 1394 is also known by the brand names FireWire (Apple), Lynx (Texas Instruments), and i.LINK (Sony). After a careful search of the commercially available options, a monochrome, progressive scan TheImagingSource DMK 31BF03-Z2A FireWire zoom camera was selected for evaluation. The specifications for these two cameras are compared in Table 1. The Sony 78B has the advantage of greater zoom magnification capability and a greater range of lens focal length, but the FireWire camera has the advantage of higher pixel resolution and lower minimum illumination.

The warm-up and intensity stability of the FireWire camera were characterized during both short-term and long-term duration tests. For the short-term pixel intensity variation test, images were acquired with a one-second interval with fixed camera settings, target, and ambient light. For the long-term test, images were acquired at a five-minute interval for about 3 hours (66 images acquired) with fixed camera settings, target, and ambient light. During the play back of the acquired images from the short-term test, the intensity value of a randomly selected pixel was monitored and was observed to remain constant. By monitoring the histogram distribution of a randomly selected region of interest (ROI) or of the whole image, it was found that the ROI's histogram stayed identical. These results indicate that the new camera is more stable than the original system. The long-term test was analyzed by subtraction of subsequently acquired images with the first image (with the camera started cold). The resulting subtracted images yielded subtracted pixel intensities of zero, indicating that there are no framegrabbing jitter or warm-up issues with this FireWire camera. The FireWire camera has neither the warm-up nor intensity stability issues that the Sony 78B block camera exhibits.

Table 1. Comparison of Sony 78B block camera and TheImagingSource (TIS) FireWire zoom camera. Wide = wide-angle. Tele = telephoto.

	SONY FCB-EX78B	**TIS DMK 31BF03-Z2**
Format	color	black & white
Pixels	640 x 480 (680K)	1024 x 768 (790K)
Optical Zoom	25x	16x
Digital Zoom	12x (300x with optical zoom)	Not Applicable
Lens Focal Length	2.4 mm (Wide) to 60 mm (Tele)	5 mm (Wide) to 45 mm (Tele)
Minimum Illumination	2.5 lux	0.05 lux
Electronic Shutter Speed	¼ to 1/10,000 sec	1/30 to 1/10,000 sec
Gain	-3 to 28 dB	0 to 36 dB
Dimensions	50.0 x 57.5 x 81.8 mm	50.2 x 50.8 x 130 mm

Table 2. Comparison of FTP volume determinations using Sony block camera and “FireWire” camera.

Camera	**Target**	**FTP Volume (cm^3)**	**Absolute Error (cm^3)**	**Relative Error (%)**
FireWire	Cone 1	272.5±1.0	7.0	2.6
Sony 78B	Cone 1	253.3±1.6	-12.2	-4.6
FireWire	Cone 2	464.0±1.8	13.6	3.0
Sony 78B	Cone 2	449.9±3.5	-0.5	-0.1
FireWire	Cone 3	155.3±1.1	-3.0	-1.9
Sony 78B	Cone 3	159.7±2.1	-11.5	-7.3

A head-to-head comparison of FTP volume determinations using both the Sony 78B camera and the FireWire camera was also performed. Three ideal targets (metal cones) were imaged under identical conditions and were analyzed using identical procedures. Five images were recorded of each target by each camera (after warm-up had been completed) and the averages and standard deviations are reported in Table 2. The average relative error for the Sony 78B camera was -4.0% while the average relative error for the FireWire camera was +1.3%. Moreover, Table 1 shows that the standard deviation (and hence volume determination reproducibility) of the FireWire camera is smaller (better) than that of the Sony 78B camera. Replacing the Sony 78B camera with the FireWire camera results in a decrease of the average FTP volume determination error.

The effect of lighting conditions on FTP volume determination was investigated. In photometry, the combination of the camera's shutter speed and of the relative aperture (*f*-number) can be expressed in terms of an exposure value (EV) [22]. Different combinations of shutter speed and aperture with the same EV value will produce images of comparable quality. The EV value is related to the exposure time *t* (in seconds) and the relative aperture *N* (*f*-number) by the equation

$$EV = \log_2 \frac{N^2}{t} \qquad \text{Eq. (4)}$$

where $\log_2$ is the base-2 logarithm. The EV is related to the illuminance *E* (total luminous flux incident on a surface per unit area) by the relationship

$$E = c\,\frac{N^2}{t} = c\,2^{EV} \qquad \text{Eq. (5)}$$

where *c* is an instrument-dependent factor that takes into account the sensitivity of the sensor. The light from the FTP projector was augmented by the light from two 500-W halogen lamps. The light intensity from the halogen lamps was decreased by using a variable alternating current transformer to decrease the voltage supplied. The light intensity was measured (in EV) by a photographic light meter. The FireWire camera was used to record FTP images of three different metal cones at a distance of about 8 ft. (2.4 m). The results of the FTP analysis of one of the cones are presented in Table 3; the results for the other two cones are similar. Both relative volume error and the quality of the reconstruction were examined. At the light intensity from the background halogen lamps increased, the contrast of the FTP fringe pattern in the acquired images decreased; on average, the FTP volume determinations errors remained the same or slightly increased. At the higher background light intensity levels, the image of the fringe pattern became degraded so much that the cone shape reconstructed from FTP displays obvious distortions. As Fig. 2 shows, even the "bad" reconstruction is clearly identifiable and differs only modestly from the "good" reconstruction. The FTP technique is robust and is relatively insensitive to ambient light levels.

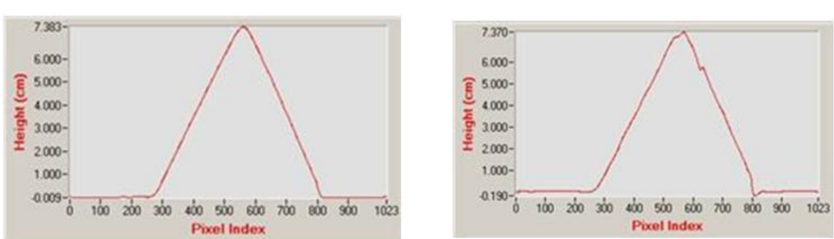

Figure 2. Example 1-D profiles reconstructed from the lighting conditions experiments. Left: cone (EV of 5.9) without distortions. Right: same cone (EV of 9.3) with obvious distortions.

Table 3. Example of FTP volume determination errors as a function of light level (in EV).

Light Level (EV)	Relative Volume Error (%)	Reconstruction Quality
5.8	2.0	Good
5.9	2.9	Good
6.1	3.4	Good
6.1	3.4	Good
6.3	4.0	Good
6.9	3.2	Good
7.5	5.0	Good
8.1	3.1	Fair
8.7	5.0	Bad
9.3	6.4	Bad
9.9	5.3	Bad

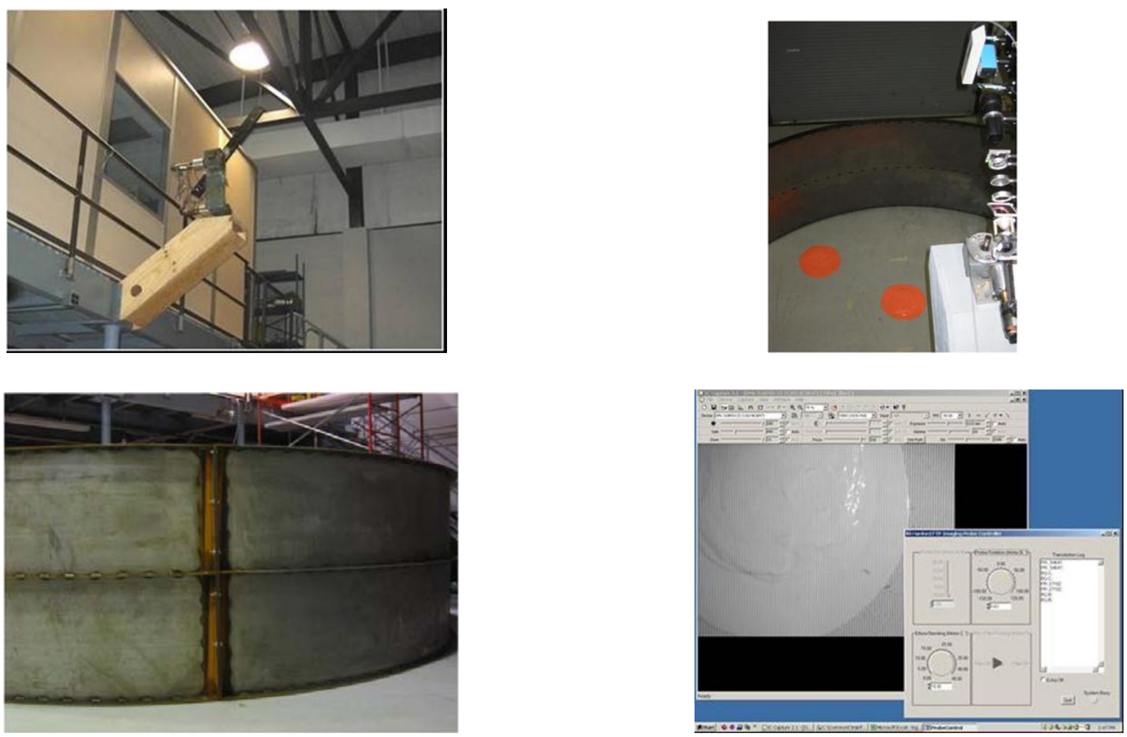

Figure 3. Top left photograph shows FTP manipulator system mounted on ICET highbay mezzanine. Top right photograph shows view from ICET highbay mezzanine of FTP manipulator system, tank wall section, and nondescript silicone rubber targets on ICET highbay floor. Bottom left photograph shows view of tank wall section from outside. Bottom right is screenshot of FTP image and computer control for FTP manipulator system.

In order to demonstrate the ability of the prototype FTP system to accurately and precisely determine the volumes of targets of interest under simulated waste tank conditions, a prototype FTP system was developed for demonstration in the ICET highbay. In order to better simulate acquiring FTP images inside a waste tank, carbon steel tank sections were fabricated to simulate a 20-ft (6.1-m) diameter, 5-ft (1.5-m) tall tank (see bottom left photograph in Fig. 3). The top photographs in Fig. 3 show the prototype FTP optical instrumentation arm mounted on a manipulator system that enables precise pan and tilt motion under computer control. The FTP system is mounted on the ICET highbay mezzanine and is being used to determine the volumes of a variety of large targets positioned at selected locations within the tank simulator. The targets consist of both targets with simple geometry and non-descript targets (see Fig. 4). The volumes of both types of targets were independently determined by traditional means. Table 4 presents the average results for five FTP volume determinations for each of four different, small non-descript targets; the volumes were determined from replicate images recorded by the prototype FTP system in the ICET highbay. The average relative error of the 20 volume determinations is 2.2% with a standard deviation of 3.6%. These small non-descript targets have been used in our previous characterization and optimization efforts [10-15] so consequently, the FTP analyst had access to their true volumes; he did not utilize that information during the volume determinations reported here, but we simply wish to point out that this portion of the FTP demonstration was not completely "blind" to the analyst.

Table 4. FTP volume determinations of small non-descript targets within single images in ICET highbay. FTP volumes are averages of five determinations of replicate images; FTP volume uncertainty corresponds to ± one standard deviation.

Target	FTP Volume (cm^3)	True Volume (cm^3)	Average Error (cm^3)	Average Error (%)
S3	2007 ± 39	1954 ± 10	53	2.7%
S4	1087 ± 16	1071 ± 6	16	1.5%
S5	425 ± 23	422 ± 5	3	0.7%
S6	672 ± 26	647 ± 4	25	3.9%
Average				2.2%

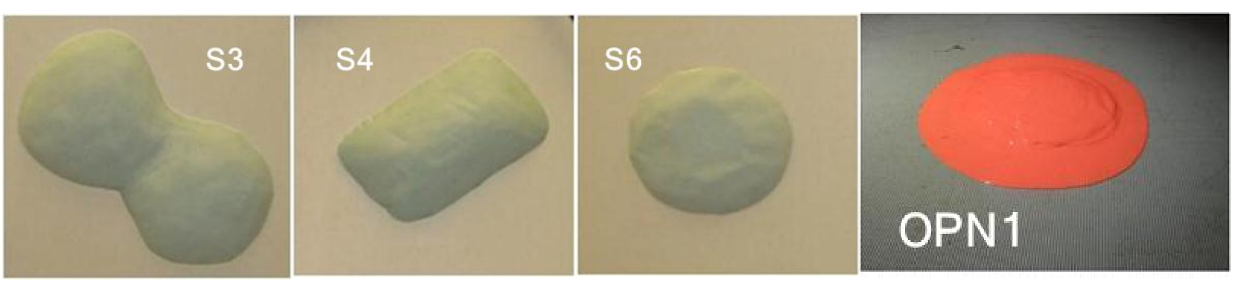

Figure 4. Photographs of some of the non-descript targets used for the FTP demonstration in the ICET highbay.

Since the residual material in the Hanford waste tanks is expected in general to extend across more than one image, we have fabricated large, non-descript, lumpy targets from silicone rubber. The volume of these non-descript targets has been independently determined to within ± 13 cm^3

(95% confidence limits) using traditional methods (water displacement). For each of four large, non-descript silicone rubber targets images have been recorded in the ICET highbay in order to provide replicate images for five volume determinations for each target. The volume determinations of six different FTP images must be stitched together in order to determine the overall volume of each target. To better simulate waste materials, the FTP analysis is being performed “blind,” i.e., the FTP analyst does not know the true volumes. To date, the FTP analyst has completed four volume determinations each of two different large, non-descript targets; these results are presented in Table 5. It can be seen that the volume errors for stitching six images together are significantly larger than those for volume determination from a single image. The larger error is due to the fact that in addition to the error of the FTP volume determination, there are also contributions to error from the stitching process and from the accuracy of the FTP manipulator position. Currently, we are in the process of characterizing the accuracy of the FTP manipulator position and the uncertainty introduced by the stitching process.

Table 5. FTP volume determinations of large non-descript targets that require the FTP volume determinations of six images to be stitched together. The uncertainty for the true volume corresponds to 95% confidence limits.

Target	FTP Volume (cm^3)	True Volume (cm^3)	Error (cm^3)	Error (%)
OPN1	1955	2190 ± 13	-235	-10.8%
OPN1	2006	2190 ± 13	-184	-8.4%
OPN1	1932	2190 ± 13	-258	-11.8%
OPN1	1950	2190 ± 13	-240	-11.0%
OPN4	1742	1785 ± 13	-43	-2.4%
OPN4	1725	1785 ± 13	-60	-3.4%
OPN4	1983	1785 ± 13	198	11.1%
OPN4	1582	1785 ± 13	-203	-11.4%

Following the successful completion of demonstration of the prototype FTP system, ICET will seek an industrial partner for technology transfer in order to facilitate ultimate deployment of an FTP probe system into radioactive waste tanks at Hanford and other DOE sites.

SUMMARY

As part of efforts to develop, characterize, and demonstrate a quantitative imaging system capable of accurate and precise determinations of residual waste volumes remaining in the Hanford tanks, the inherent instrumental volume determination uncertainty has been reduced by replacing the color block camera that had previously used with a monochrome FireWire camera. Reliable volume determinations under a wide variety of lighting conditions indicate that image reconstruction distortions can occur at high illuminations; however, small variations in background illumination will not degrade the fringe pattern image. A prototype of the system is being used to demonstrate the ability of the FTP technique to accurately and precisely determine volumes of interest under simulated waste tank conditions.

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