Characterization and Optimization of Quantitative Waste Volume Determination Technique for Hanford Waste Tank Closure -- 10035

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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 measure how much residual material is left in each waste tank and to quantify the uncertainty in that measurement.

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. A fringe pattern is projected onto the target surface and then observed from a different viewing angle. The observed fringe pattern is distorted due to variations in the height of the surface. From these distoprtions, 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. We report our efforts to characterize the accuracy and precision of quantitative volume determination using FTP and our use of these results to optimize the FTP system for deployment within Hanford waste tanks. The efforts reported in this paper concentrate on characterizing uncertainties introduced by imager stability and by imager lens distortions.

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) [1-6].

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 [7]. A submersible version of the ICET FTP system has been deployed in the Oak Ridge Research Reactor pool to characterize aluminum pit corrosion [8]. To date, the ICET FTP system has obtained preliminary results utilizing conditions appropriate for the Hanford waste tanks [9-13].

FOURIER TRANSFORM PROFILOMETRY METHOD

Fourier transform profilometry (FTP) is a non-contact, 3-D shape measurement technique [14-17]. 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.

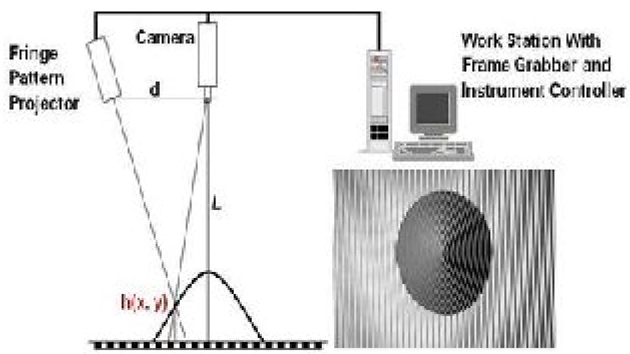


Figure 1. Diagram illustrating the principle of Fourier-transform profilometry.

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.
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 [15], 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

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

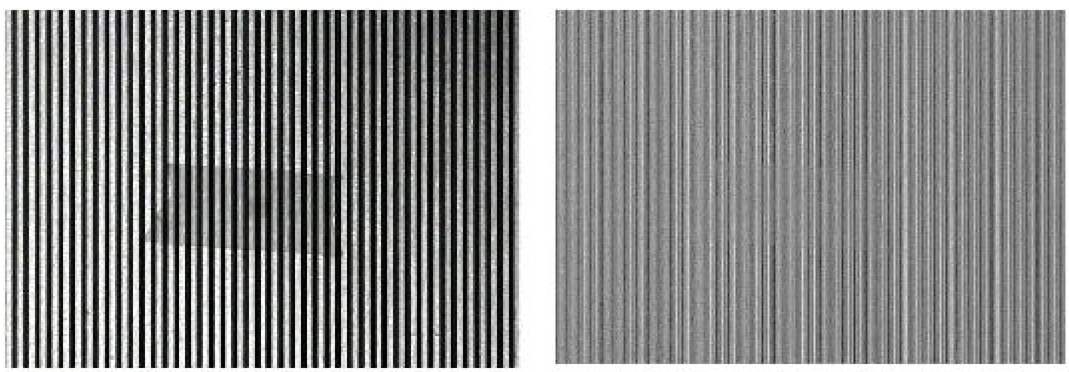
and $\Delta\Phi_p$ stands for the phase shift that a single pixel in the acquired image is able to resolve, n_{line} is the total number of repeating fringe lines in the image, and X_{pixel} is the horizontal image dimension (in pixels). Obviously, the L_0 and d parameters, the density of fringe lines, 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.

TECHNICAL FEASIBILITY STUDY

In order for our Hanford collaborators to be able to quantitatively compare the FTP technique with other applicable volume measurement techniques, we were requested to document in a technical feasibility report the performance of our current ICET FTP system as a function of operational parameters under simulated conditions applicable for deployment in a Hanford radioactive waste tank and also what is possible in order to further improve the precision and accuracy of the technique. We report our most recent results, including those to extend our volume determination uncertainty investigations to targets larger than a single image. This effort requires us to characterize the distortions introduced by the imager's lens.

We have investigated the warm-up time and stability of our imager. A fringe pattern was printed onto a transparency and mounted onto a wall. The imager was turned on and under computer control, automatically recorded an image every five minutes. Fig. 2(a) shows the first image recorded just after the imager had been turned on. Fig. 2(b) shows the result obtained by subtracting the first image recorded from the image recorded after the imager had been on for 45 minutes. If there had been no changes, then Fig. 2(b) would have been completely black. However, Fig. 2(b) shows a black-and-white fringe pattern, indicating that the fringe pattern [Fig. 2(a)] has in effect systematically changed with time.



(a.) (b.)

Figure 2. Imager stability study. (a.) Image of a printed fringe pattern recorded just after turned camera on. The dark area in the center is double-stick tape that was used to mount the transparency to a wall. (b.) Result obtained by subtracting image (a) from image recorded after imager had been on for 45 minutes.

Figure 3 shows how the intensity difference changes as a function of time for different imagers. The intensity difference can be related to the FTP phase change and hence with FTP height (volume) determinations. Positive intensity differences correspond to the "white" fringes in Fig. 2(b) and negative intensity differences correspond to the "black" fringes in Fig. 2(b). It is seen that the SONY FCB-EX78B (color) camera has a warm-up time of at least a half hour, while the SONY FCB-EX45MC (monochrome) camera has a shorter warm-up time. Moreover, the intensity differences are larger for the 78B camera than for the 45MC camera. The experiment has been repeated using a different 78B camera and the results were qualitatively similar to those of the first 78B camera. We investigated whether or not cooling by a fan would decrease the intensity difference; we found that for the 45MC camera, cooling by a fan does not significantly affect the results. Experiments were also performed with the 78B camera and our prototype projection system. The intensity differences were slightly larger (worse) than those for the 78B. Without cooling, the Ronchi filter (which is used to generate the fringe pattern) has a surface temperature change of about 55°C and a warm-up time of about 10-15 minutes; with cooling, the surface temperature change of the Ronchi filter is restricted to about 20°C and the warm-up time reduced to about 5 minutes. For both the imager and Ronchi filter, FTP images should not be recorded until the warm-up time has passed and the system is at thermal equilibrium in order to insure reproducible conditions and to minimize measurement uncertainty.

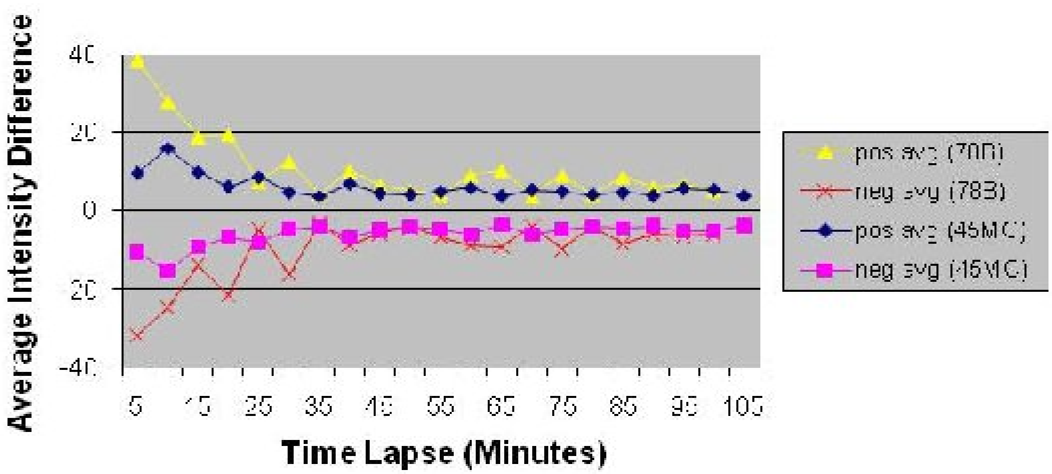


Figure 3. Intensity differences (positive and negative) relative to an image recorded five minutes earlier using SONY FCB-EX78B (color) and SONY FCB-EX45MC (monochrome) cameras as function of time (in minutes) since the cameras were turned on.

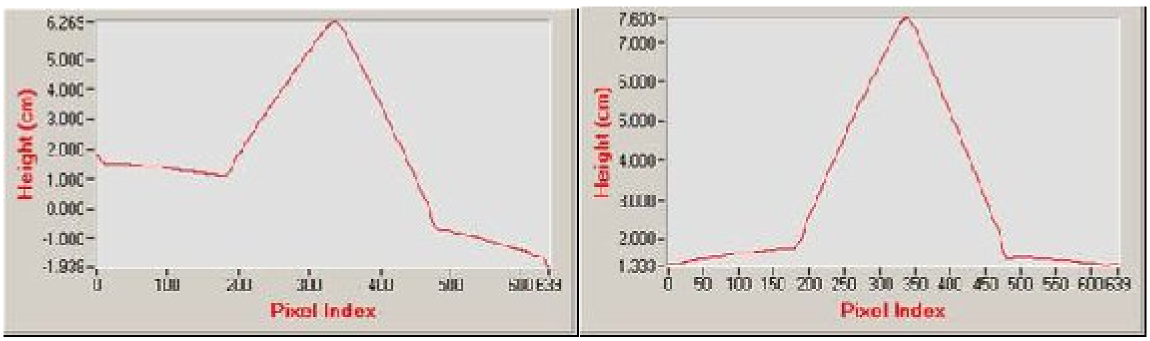
Table 1. Comparison of fluctuations in intensity differences (relative to first image recorded) at thermal equilibrium (times ≥ 45 minutes after imager turned on) for SONY FCB-EX78B (color) and SONY FCB-EX45MC (monochrome) cameras.

Imager	Intensity Difference	Fan	Average	Std Dev
78B	Positive	None	80.83	4.53
78B	Negative	None	-87.60	4.48
45MC	Positive	Off	11.91	0.10
45MC	Negative	Off	-14.85	1.57
45MC	Positive	On	13.90	0.56
45MC	Negative	On	-14.68	0.91

The data in Fig. 3 can also provide an indication of the imager stability at thermal equilibrium. If we assume that both imagers are at thermal equilibrium by 45 minutes after they have been turned on, then the standard deviation of the intensity differences for times ≥ 45 minutes is an indication of the imager stability. Table 1 compares the results for these two imagers. We see that cooling does not significantly change the stability (standard deviation) of the 45MC imager and that the 78B imager is less stable (larger standard deviation) and hence will have significantly greater volume measurement uncertainty than the 45MC imager. The SONY FCB-EX78B imager was originally chosen for FTP use because it is similar to imagers currently used in Hanford waste tank retrieval efforts.

An extended duration test was performed on the SONY FCB-EX78B block camera. Images were periodically recorded under computer control and under uniform lighting conditions. The variation of the intensity of a single fringe was determined. The difference between the maximum intensity for a given pixel and the minimum intensity for the same pixel was about 10 (out of a range of 0 to 255) so this corresponds to about a 4% variation in intensity. Because intensity changes are very likely related to phase changes and hence to apparent height (depth) changes, this variation could contributes to the FTP volume measurement uncertainty. The digital image obtained by the camera is converted to an analog signal for transmission to the image acquisition computer, where the image is converted from analog format back into digital format for storage. We attribute this intensity fluctuation to fluctuations associated with the analog-to-digital conversion process. The extended duration results along with the average intensity difference results (Fig. 3, Table 1) strongly indicate that another imager other than a SONY FCB-EX78B should be used in order to decrease the volume measurement uncertainty. In an attempt to eliminate this source of volume measurement uncertainty, we have begun investigating the feasibility of utilizing cameras that use direct transmission of the digital signal from the camera to the computer without an intermediate conversion to a different format.

The FTP technique, in effect, requires that an image of the target area without the target ("reference image") be compared with an image of the target area with the target. In practical situations, such as inside the Hanford waste tanks, it is not possible to record images without the targets (residual waste) present. Therefore it is necessary to use computers and "as-built" drawings to generate appropriate synthetic (computer-generated) reference images. Much of our current effort has involved the use of synthetic reference images to analyze real FTP images. Our first effort yielded the result shown in Fig. 4(a); although the profile of the target (cone) is correct, there is a tilted background that produces an incorrect overall volume. We found that the fringe pattern in the real image was slightly tilted relative to the fringe pattern in the synthetic image because the Ronchi filter used to generate the fringe pattern for the real image was tilted. Rotating (tilting) the fringe pattern in the synthetic image to produce that in the real image yielded the result shown in Fig. 4(b), where there is significant improvement over the result of Fig. 4(a), but there is still some residual error in the "wings." Subsequent investigation has revealed that the distribution of the fringe pattern and also the distribution of the intensity in the real image are not uniform. The discrepancy between real and synthetic images is due partially to non-uniform fringe pattern intensity in the real image (due to the Ronchi filter and the FTP illumination/projection system) and partially due to distortion introduced by the camera lens. Initial efforts to address the non-uniform intensity distribution have concentrated on development of an adaptive software program that adjusted the intensity of the synthetic reference image (which is uniformly distributed) according to non-uniformly distributed intensity in a real target image. In the adaptive approach, each pixel was adjusted uniquely. The intensity average in a pixel's local neighborhood was compared with its counterpart in the target image. Then the difference was added back to the pixel to achieve the adjustment. To address the camera lens distortion, software has been developed incorporating both Brown's model and the USGS model for barrel and pincushion lens distortions [18]; we are now seeking the optimum set of parameters in order to compensate for the lens distortion. The capability to compensate for lens distortion is important since each lens has a slightly different distortion pattern and it will be necessary to be able to determine the optimum set of lens distortion parameters whenever the lens and/or camera is changed. An indication of our current level of success in these efforts is presented in Table 2, where the FTP results obtained from analyzing the same real target image with a real reference and with an intensity-adjusted synthetic image are compared. It is seen that the FTP volume measurement error with a synthetic reference image is only slightly worse than with a real reference image. Efforts continue to further improve our capability.



(a) (b)

Figure 4. (a.) 1-D reconstructed profile of real image of a cone analyzed using synthetic reference image. (b) 1-D reconstructed profile of real image of a cone analyzed using synthetic image with correctly tilted fringes.

Table 2. Results obtained from analyzing a real target image using different reference images.

Reference Image	Truth Volume (cm^3)	FTP Volume (cm^3)	Error (%)
Real Reference	265.5	256.0	-3.6
Synthetic with Grid Line and Intensity Adjustments	265.5	254.7	-4.1

In order to attempt to reduce the FTP analysis artifacts, five different windowing schemes (Hann, sine, Bartlett, Gauss, and Blackman) were implemented and applied to the FTP process (for the region of interest in the fast Fourier transform (FFT) spectrum before generating the phase maps). The five windowing schemes yielded similar results. Overall, the Blackman and Hann schemes worked slightly better. However, the negative effects of the artifacts were very limited no matter what windowing scheme was used.

SUMMARY

We have initiated an assessment of the Fourier transform profilometry (FTP) technique in order to characterize the accuracy and precision of quantitative volume determination using FTP and to use these results to optimize the FTP system for residual waste determinations within Hanford waste tanks; recent results are presented in this paper. We achieve FTP volume determinations with relatively small errors. Measurement uncertainty can be minimized by ensuring that FTP images are only recorded after instrumental warm-up when the system is at thermal equilibrium. Our imager stability investigation suggests that more reliable FTP volume determinations can be obtained with an imager other than a SONY FCB-EX78B (which we had previously utilized because it is similar to imagers currently used for Hanford waste tank retrieval efforts). We are currently investigating the feasibility of utilizing other imagers. We have also begun an investigation to understand and minimize factors that affect our ability to use FTP to determine the volumes of targets using synthetic reference images. This capability is essential for quantitatively applying FTP to Hanford waste tank residual volume determination. Our current effort concentrates on characterizing the distortions introduced into FTP images by our imager lens system.

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