Technical Performance Capability of Fourier Transform Profilometry for Quantitative Waste Volume Determination under Hanford Waste Tank Conditions – 9333

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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 chemical makeup of the residue.

The Institute for Clean Energy Technology (ICET) at Mississippi State University is currently developing a quantitative in-tank inspection system based on Fourier Transform Profilometry (FTP). FTP is a non-contact, 3-D shape measurement technique. 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. We report the results of a technical feasibility study to document the accuracy and precision of quantitative volume determination using the Fourier transform profilometry technique 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)[1-5].

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 [6]. A submersible version of the ICET FTP system has been deployed in the Oak Ridge Research Reactor pool to characterize aluminum pit corrosion [7]. To date, the ICET FTP system has obtained preliminary results utilizing conditions appropriate for the Hanford waste tanks [8-10].

METHOD OF FOURIER TRANSFORM PROFILOMETRY

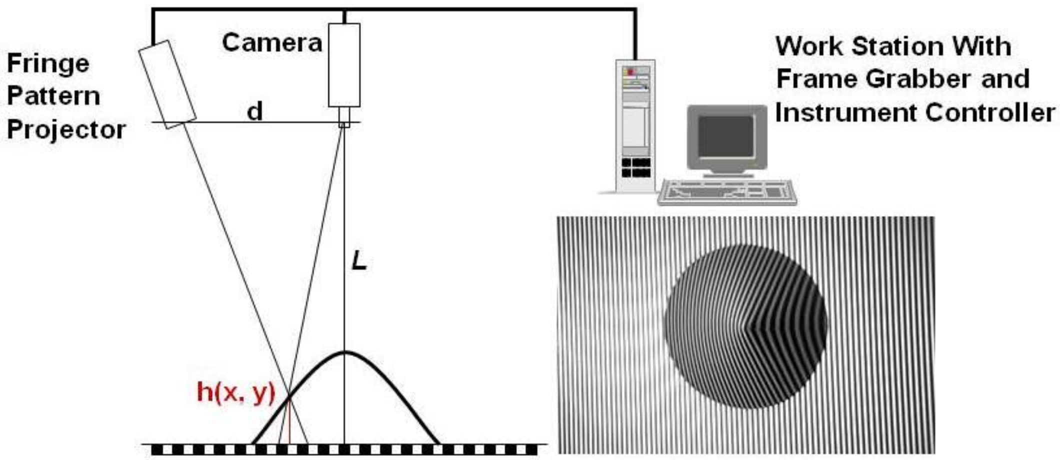


Figure 1. Diagram illustrating the principle of Fourier-transform profilometry.

Fourier transform profilometry (FTP) is a non-contact, 3-D shape measurement technique [11]. 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 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.

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 [11], 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 results to date.

There are two generally accepted measurement uncertainty models in current use: the American Society of Mechanical Engineers' (ASME) Performance Test Code (PTC) and the International Organization for Standarization's (ISO). The ASME model classifies uncertainties as either bias or random. The ISO model classifies them as types A and B. Type A uncertainties are those based on statistical analysis of measurements, and type B are everything else. Most experts believe that both the ASME and ISO models should give the same final answer for the combined uncertainty. We have chosen to use the ASME model.

For the FTP method, the basic equation is Eq. (1). The output of the FTP measurements is calculated from four quantities (phase shift $\Delta\Phi$, instrument-to-target distance L_0, separation between projecting optics and receiving optics d, and fringe frequency f_0). There is an uncertainty associated with each of these quantities.

The protocol used for the error propagation requires the partial derivatives of the right hand side of Eq. (1) with respect to each measured quantity on which it depends. Thus,

$$\frac{\partial h}{\partial L_0} = \frac{\Delta\phi}{\Delta\phi - 2\pi f_0 d} = \frac{h}{L_0} \qquad \text{Eq. (4)}$$

$$\frac{\partial h}{\partial(\Delta\phi)} = \frac{L_0}{\Delta\phi - 2\pi f_0 d} - \frac{L_0\,\Delta\phi}{(\Delta\phi - 2\pi f_0 d)^2} = \frac{h}{\Delta\phi} - \frac{h}{\Delta\phi - 2\pi f_0 d} \qquad \text{Eq. (5)}$$

$$= \frac{h}{\Delta\phi} - \frac{h^2}{L_0\,\Delta\phi} = \frac{h}{\Delta\phi}\left(1 - \frac{h}{L_0}\right)$$

$$\frac{\partial h}{\partial f_0} = -\frac{L_0\,\Delta\phi}{(\Delta\phi - 2\pi f_0 d)^2}(-2\pi d) = \frac{2\pi h d}{\Delta\phi - 2\pi f_0 d} = \frac{2\pi h^2 d}{L_0 \Delta\phi} \qquad \text{Eq. (6)}$$

and

$$\frac{\partial h}{\partial d} = -\frac{L_0\,\Delta\phi}{(\Delta\phi - 2\pi f_0 d)^2}(-2\pi f_0) = \frac{2\pi h f_0}{\Delta\phi - 2\pi f_0 d} = \frac{2\pi h^2 f_0}{L_0 \Delta\phi} \qquad \text{Eq. (7)}$$

These partial derivatives are sometimes referred to as "influence coefficients," because they describe how much effect an error in measuring each quantity ($\Delta\phi$, L_0, d, and f_0) will have on the final determination of h. These influence coefficients apply to both bias and random errors. Multiplying each influence coefficient by the estimated uncertainty in the corresponding measurement gives the contribution to the total uncertainty.

To illustrate, consider the case of a camera-to-object ("standoff") distance L_0 of 7.567±0.01 m, a camera-to-projector distance d of 22.2±0.3 cm, and a fundamental frequency f_0 of 1.05±0.02 lines/cm. The influence coefficients are given in Table 1 below. It can be seen that in this typical case, the greatest contributions to error in the height *h* are due to the effects of phase shift uncertainty and of baseline uncertainty.

Table 1. "Influence coefficients" for above example, showing the sensitivity of FTP height determination as a function of experimental parameters. The abbreviation "wrt" means "with respect to."

	Influence Coefficient
Partial h wrt phase shift $\Delta\Phi$	–0.03523
Partial h wrt standoff distance L_0	+0.003357
Partial h wrt fringe frequency f_0	–0.00017
Partial h wrt baseline d	–0.07864

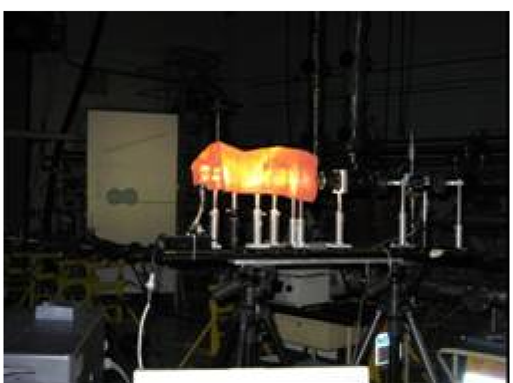
The resulting error contributions are given in Table 2. The resulting overall error estimate is $6.163\text{x}10^{-3}$ meters with the major contribution being from the phase shift. The two largest contributions to the error are related to determination of the phase shift and to the baseline d (i.e., camera-to-projector separation.) Determination of the phase shift $\Delta\Phi$ will be a function of camera resolution, image contrast, and also the details of the FTP analysis; consequently, reduction of the phase shift error contribution would require using a camera that simultaneously provides higher pixel resolution and higher image contrast while still complying with space restrictions. Because of the space constraints introduced by the requirement that the probe system fit through a 10-cm (4") ID riser, an FTP probe can only contain one grid-projection Ronchi filter; therefore, once the appropriate line spacing for the Ronchi filter has been determined, no further optimization of the fringe frequency f_0 is possible for this application. Consequently, we did not investigate the effect of fringe frequency f_0 upon volume measurement error. As part of our technical feasibility evaluation, we experimentally investigated the effect of camera-to-projector separation d upon the volume determination results of the operating parameters over which we have control, this contributes most to the volume determination uncertainty.

Table 2. Absolute errors (in m) resulting for example above.

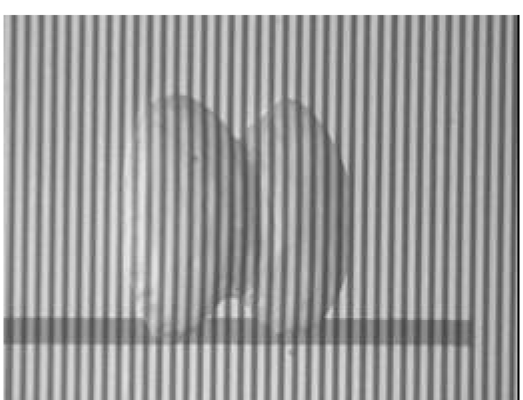
	Absolute Error
Phase shift $\Delta\Phi$	6.149×10^{-3}
Standoff distance L_0	3.36×10^{-5}
Fringe spatial frequency f_0	3.31×10^{-4}
Rangefinder baseline d	2.36×10^{-4}

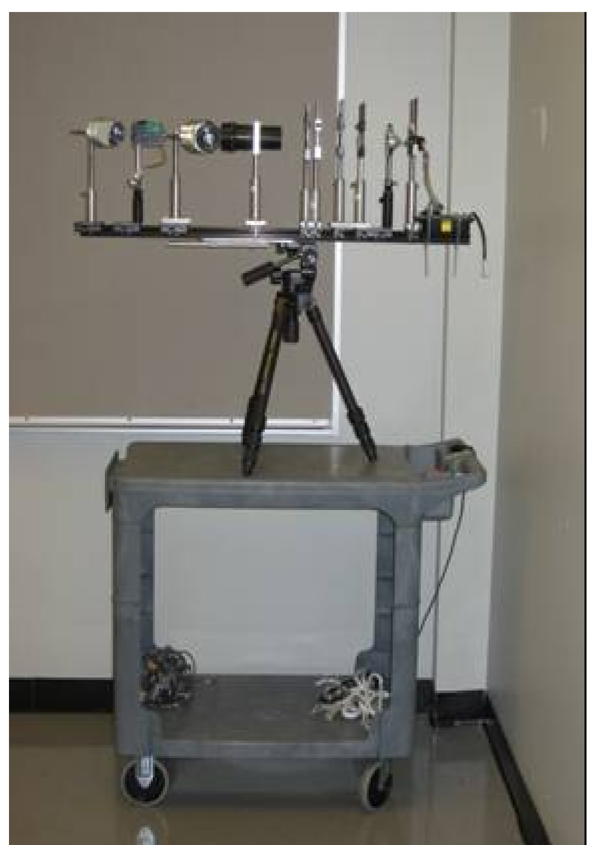
The 200-series Hanford waste tanks are typically ~22.9 m (75’) in diameter with an internal height of ~11.7 m (38’5”). An FTP probe would be deployed through a 10-cm (4”) inside diameter (I.D.) riser located 2.7 m (9’) off center. The most challenging location at which to determine residual waste volumes is the “junction” where the upright wall joins the tank floor diametrically opposite the riser. If the FTP system is 7.6 m (25’) above the tank bottom, then the far “junction” is ~16.1 m (52.8’) away at an angle of ~62° from the vertical. Therefore, we have experimentally determined our ability to quantitatively determine the volume of non-descript objects located ~16.2 m (53’) from our FTP system at angle of ~62°. The experiments were performed in ICET’s high bay area with the lights off, as shown in Fig. 2. Three different non-descript targets from our previous development efforts [8,9] were utilized and each was recorded in four different rotational configurations so that a total of 12 independent determinations of volume were made. The “true” volumes of the non-descript targets were determined independently by traditional (volume-displacement) methods with a relative uncertainty of ~1% [8,9].

The results for a camera-to-projector distance of 46.1 cm are presented in Table 3. The overall average measurement error is 5.2%. There is some variation in error from target to target: the smallest target (S6) had the largest average relative error (7.2%), followed by the largest target (S3) with 6.0% average error, and the middle-size target (S4) with the smallest average error



(a)





(b) (c)

Figure 2. (a) Photograph of ICET FTP components on optical rail viewing non-descript, grey targets on white background at distance of 16.2 m (53') and angle of ~62°. A cloth shroud has been placed over the light source to minimize the amount of non-fringe pattern light on the target. (b) Example image of a non-descript target with fringe lines projected on its surface, acquired using the setup in (a). (c) ICET FTP components on optical rail as utilized in the setup in (a).

Table 3. Comparison of FTP-determined ("measured") and true volumes for three different non-descript targets. Each target was recorded in four different rotational orientations. The separation between camera and projector was 46.1 cm (~18").

Target	**True Volume (cm^3)**	**Measured Volume (cm^3)**	**Error (cm^3)**	**Error (%)**
S3	1954±10	2057	+103	+5.3
S3	1954±10	2039	+85	+4.4
S3	1954±10	2085	+131	+6.7
S3	1954±10	2105	+151	+7.7
S4	1071±6	1089	+18	+1.7
S4	1071±6	1129	+58	+5.4
S4	1071±6	1081	+10	+0.9
S4	1071±6	1087	+16	+1.5
S6	647±4	683	+36	+5.6
S6	647±4	686	+39	+6.0
S6	647±4	695	+48	+7.4
S6	647±4	711	+64	+9.9
Average				+5.2

S3 **S4** **S6**

Figure 3. Photographs of the three non-descript targets used.

(2.4%). Fig. 3 shows photographs of these three non-descript targets. S6 is a "circular" target with sloping edges that is flattened on top. S4 is a "rectangular" target with sloping edges that is "rounded" at the top. S3 has the most irregular geometry, consisting of two "circular" "piles" joined together.

As noted above, the height determination is most sensitive to the separation d between the camera and the projector (after determination of phase shift). Therefore, we have investigated the effect of camera-to-projector distance d upon the volume measurement error; the results are summarized in Table 4. The results show an alternation of the sign of the error with d, but that once d has been set, all the errors have the same sign. This suggests a systematic error whose origin we are in the process of investigating. The results are consistent with a decrease in the average error with increasing camera-to-projector distance d, as is predicted by the sensitivity analysis. The magnitude of the error decreases with decreasing target volume. Consequently, the relative error should be independent of volume. Table 5 shows that there is no obvious pattern for the relative error as a function of volume; this is not inconsistent with the relative FTP volume error being independent of volume. Fig. 4 shows that the magnitude of the average error decreases with increasing camera-to-projector distance d.

Table 4. Comparison of average absolute errors for the selected non-descript targets as a function of the camera-to-projector distance ("baseline") d for d = 21.8 cm (~ 9"), d = 33.4 cm (~13"), and d = 46.1 cm (~18"). The uncertainties are one standard deviation. In the last column, the averages of the absolute values of the absolute errors are presented.

Target	True Volume (cm^3)	Error d=21.8 cm (cm^3)	Error d=33.4 cm (cm^3)	Error d=46.1 cm (cm^3)	Average
S3	1954±10	+221±57	-144±70	+118±29	161
S4	1071±6	+98±24	-108±19	+26±22	77
S6	647±4	+63±35	-38±25	+47±13	49
Average		+127	-97	+64	96

Table 5. Comparison of average relative errors for the selected non-descript targets as a function of the camera-to-projector distance ("baseline") d for d = 21.8 cm (~ 9"), d = 33.4 cm (~13"), and d = 46.1 cm (~18"). In the last column, the averages of the absolute values of the relative errors are presented.

Target	True Volume (cm^3)	Error d=21.8 cm	Error d=33.4 cm	Error d=46.1 cm	Average
S3	1954±10	+11.3%	-7.4%	+6.0%	8.2%
S4	1071±6	+9.1%	-10.0%	+2.4%	7.2%
S6	647±4	+9.8%	-5.9%	+7.2%	7.6%
Average		+10.0%	-7.8%	+5.2%	7.7%

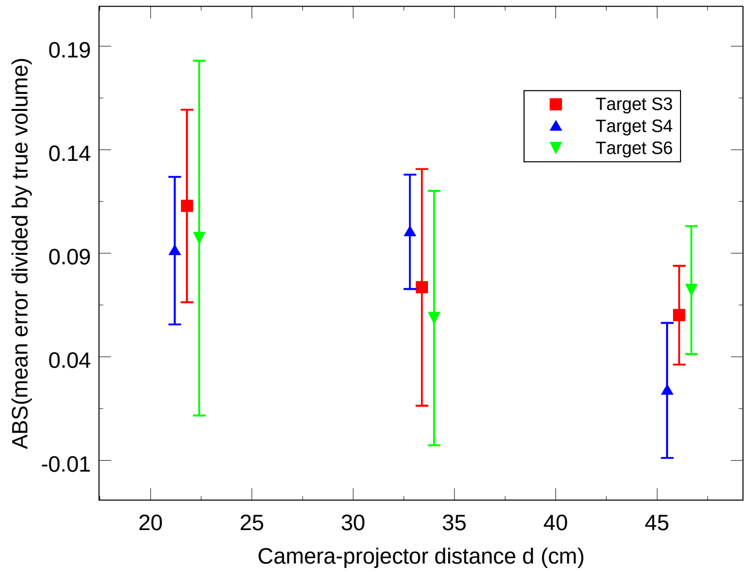


Figure 4. Plot of the magnitude of the average absolute error divided by the true volume (giving the average relative error) as a function of the camera-to-projector distance d. Horizontal dithering has been applied to the data to separate the data points and 95% confidence-limit error bars.

CONCLUSIONS

We have initiated a technical feasibility assessment of the Fourier transform profilometry (FTP) technique for determining the volume of residual waste in Hanford radioactive waste tanks; preliminary results are presented in this paper. We find that the relative error is independent of volume. The effect of the camera-to-projector separation d on the FTP measurement error was investigated for a series of separation that span the range from the minimum feasible with the current equipment to the maximum feasible for appropriate articulation of an FTP probe arm that can be inserted through a 10-cm (4”) ID riser. We find that the FTP error decreases with increasing camera-to-projector separation.

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