Performance Evaluation of Fourier Transform Profilometry for Quantitative Waste Volume Determination Under Simulated Hanford Waste Tank Conditions

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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 objective of Mississippi State University's Institute for Clean Energy Technology's (ICET) efforts is to develop, fabricate, and deploy inspection tools for the Hanford waste tanks that will (1) be remotely operable; (2) provide quantitative information on the amount of wastes remaining; and (3) provide information on the spatial distribution of the residual waste. A collaborative arrangement has been established with the Hanford Site to develop probe-based inspection systems for deployment in the waste tanks.

ICET is currently developing an 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 have completed a preliminary performance evaluation of FTP in order to document the accuracy, precision, and operator dependence (minimal) of FTP under conditions similar to those that can be expected to pertain within Hanford waste tanks. Based on a Hanford C-200 series tank with camera access through a riser with significant offset relative to the centerline, we devised a testing methodology that encompassed a range of obstacles likely to be encountered "in-tank." These test objects were inspected by use of FTP and the volume of the test objects determined. The volumes of non-descript test objects were independently determined and were not known to the FTP operators. Several stages of testing are ongoing with successive stages imposing aspects that present increasing difficulty and increasingly more accurate approximations of in-tank environments.

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)[1-4].

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). FTP was developed by ICET for inspection of an off-line Joule-heated melter at the West Valley Demonstration Project [5,6]. A submersible version of the ICET FTP system has been deployed in the Oak Ridge Research Reactor pool to characterize aluminum pit corrosion [7]. 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 of the target surface, thus reproducing the profile of the target accurately. ICET has previously demonstrated that its FTP system can quantitatively estimate the volume and depth of removed and residual material to high accuracy. To date, the ICET FTP system has obtained preliminary results utilizing conditions appropriate for the Hanford waste tanks. A prototype telescoping probe design for FTP deployment within the Hanford tank has already been completed and is being tested.

METHOD OF FOURIER TRANSFORM PROFILOMETRY

Fourier transform profilometry (FTP) is a non-contact, 3-D shape measurement technique [8]. 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.

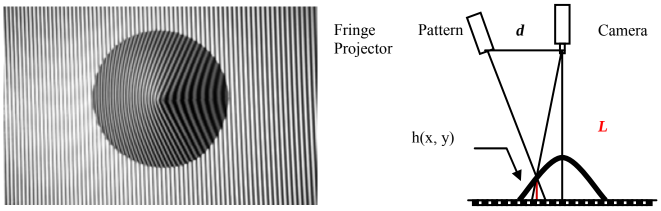

Figure 1. Diagram illustrating the principle of Fourier-transform profilometry.

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 [8], the height distribution of the target surface is easily calculated by using Eq. (1).

$$h(x,y)=\frac{L\Delta\Phi(x,y)}{\Delta\Phi(x,y)-2\pi df_0} \qquad \text{Eq. (1)}$$

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).

$$\Delta h_p = L\Delta\phi_p / [\Delta\phi_p - 2\pi df_o] \qquad \text{Eq. (2)}$$

where

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

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.

Two key issues are involved in FTP. The first one is that there is a slope limitation to height measurement. With *L* (the distance from the camera to the reference surface) and *d* (the distance between the camera and the projector) fixed, the maximum slope that can be measured is one third of *L*/*d*. The other key issue is phase unwrapping [9,10]. The phase values generated from inverse Fourier transforms are all wrapped in the range of -π to π, which causes discontinuities of 2π in phase images. These discontinuities must be resolved by applying phase unwrapping techniques to the wrapped phase data. Choice of a certain phase unwrapping algorithm may have remarkable impact on the accuracy and efficiency of the FTP computation.

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.

OVERVIEW OF MULTI-STAGE EVALUATION TESTING PLAN

It is desirable to evaluate the performance of ICET's FTP inspection system under simulated conditions such as will be imposed by the underground waste tank environment. Considering a Hanford waste tank with camera access through a riser with significant offset relative to the centerline, we devised a testing methodology that encompassed a range of obstacles likely to be encountered "in-tank". The basic methodology is to first categorize the tank floor and sidewall surfaces according to angles of incidence to "clean tank" surface; distances from the camera to the surface; tank surface curvature; and surface area coverage provided by the structured light projector/camera field-of-view (FOV). Selected test objects are then placed onto a surface in a manner that mimics the residual waste found "in-tank." Photos of the proposed simulated scenes were sent to our Hanford collaborators for their comments/suggestions/approval prior to commencement of testing. These nondescript test objects were inspected by use of FTP and the volume of the test objects determined.

Testing at ICET will involve a series of stages, with successive stages imposing aspects that present increasing difficulty and increasingly more accurate approximations of in-tank environments. The first stage (reported here) involves utilizing single ICET FTP images to make volume determinations of selected objects on a flat tank floor [11]. The second stage will involve stitching together the results of volume determinations from single ICET FTP images of objects on a flat tank floor to provide a determination of the total residual volume. The third stage will use single FTP images to determine the volume of objects on a curved tank floor. The fourth stage will employ stitching together of objects on a curved tank floor to provide a determination of the total residual volume. In order to utilize available space during the first four testing stages, the simulated tank bottoms are viewed horizontally rather than vertically, i.e., the simulated tank "bottoms" are actually "walls" rather than "floors." The final stage of FTP performance evaluation at ICET will involve demonstration of the ICET FTP robotic probe system to simulate deployment in a waste tank. This stage will be followed by demonstration of the ICET FTP system at Hanford's Cold Test Facility (CTF).

All the stages include both "known" targets (for which at least some of the dimensions are known *a priori*) and nondescript targets (whose dimensions and volumes are not known to those performing the FTP analysis). The purpose of the "known" targets is to simulate objects that frequently occur in waste tanks, such as hoses, weld marks, and instruments/objects that having served their purpose, have been left on the waste tank floor. The "known" targets were included at the request of our Hanford collaborators. The volumes of the nondescript targets have been independently determined by traditional methods (water displacement and by weight using the density of the material).

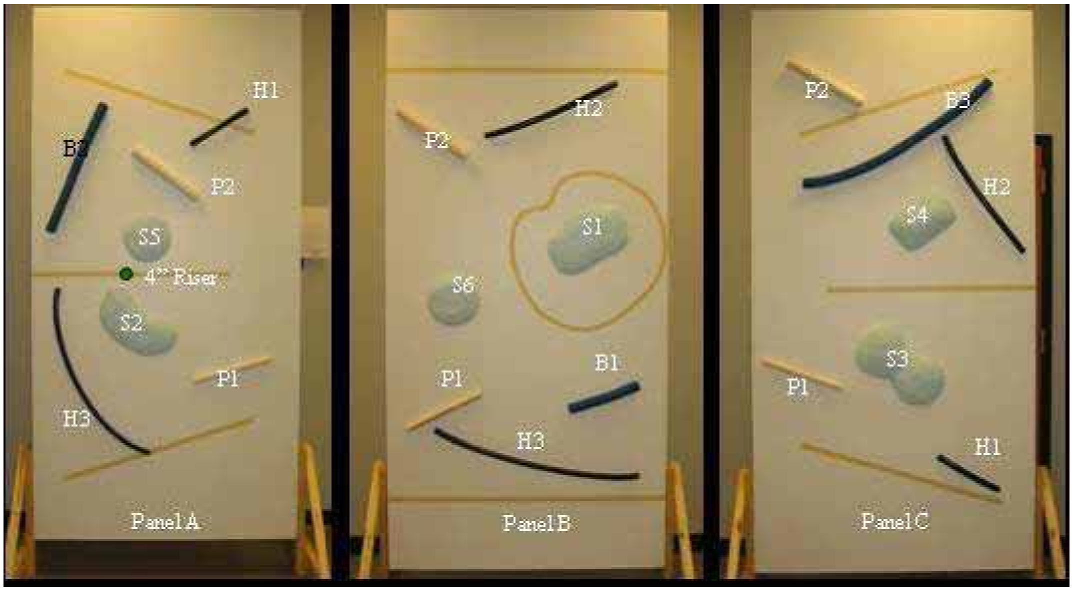

Figure 2. The three Stage 1 panels with all targets, non-descript and "known," mounted on them.

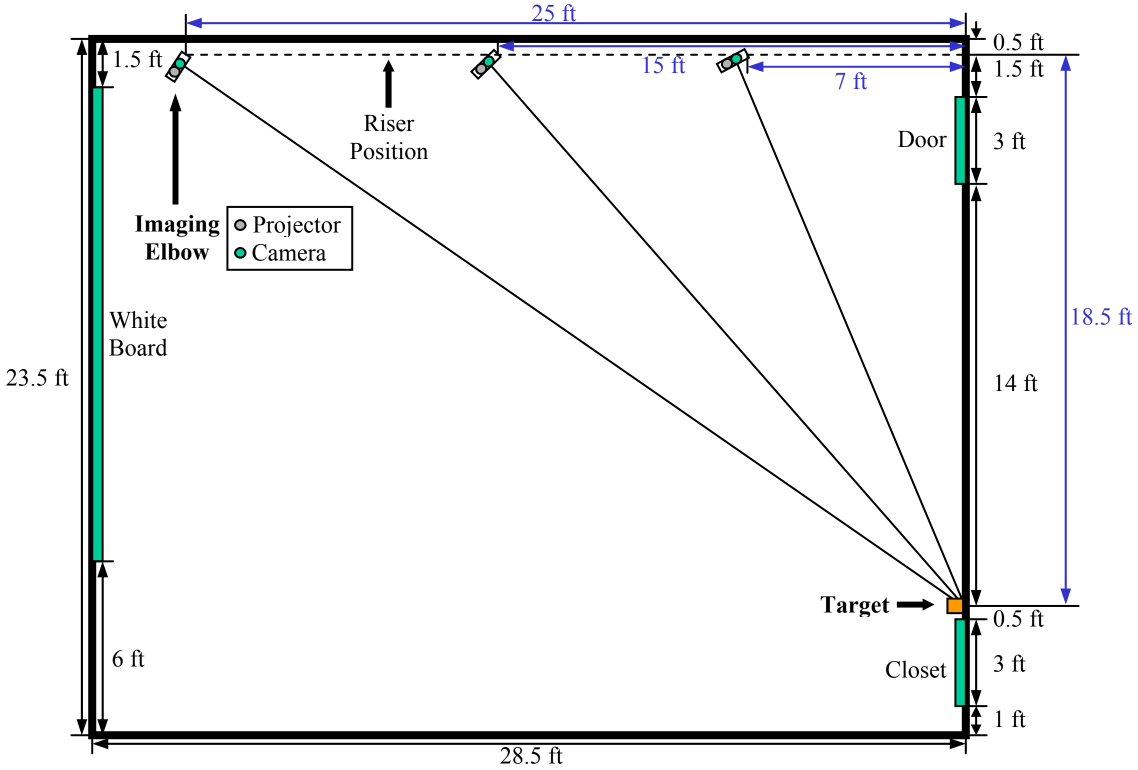

Figure 3. Schematic showing viewing arrangements for the location of Panel C. Panels A and B are also located on the right wall between the closet and the door.

There were altogether six nondescript targets prepared for Stage 1 volume determination with the ICET FTP system. The heights of the nondescript targets were low in order to simulate low piles of heights likely to be found within Hanford waste tanks. The heights of the nondescript targets were not uniform. The maximum nondescript target heights (Fig. 2) were: Panel A, target S2 < 7/8" (< 22.2 mm) and target S5 < 5/8" (< 15.9 mm); Panel B, target S1 < 11/16" (< 17.5 mm) and target S6 < 15/16” (< 23.8 mm); and Panel C, target S3 < 1 5/8” (< 41.3 mm) and target S4 < 1 ¾” (< 44.5 mm). There were also some targets with known volumes or at least some known dimensions (“known” targets, e.g. pipes) to be measured. These targets were mounted on three rectangular flat panels placed upright against a wall, as shown in Fig. 2. The three panels were utilized to simulate sections of the bottom of a 20’-diameter Hanford waste tank. Specifically, Panel A simulates the tank bottom right under a 4”-diameter riser (located 8.5’ off the center of the tank) through which the FTP imaging elbow would be inserted; Panel B is 9’ off the riser and is approximately at the center of the tank; and Panel C is 18.5’ off the riser, representing the edge of the tank bottom far off the riser.

The FTP imaging elbow was set up on a tripod on a cart. The cart was placed at a certain distance away from Panel A, with the camera looking straight forward at the 4” riser mark (see Panel A in Fig. 3). For data acquisition, the cart was only moved forward or backward, along the direction perpendicular to Panel A. To look at targets on Panels B and C, the camera was tilted toward those panels. This procedure simulates operation in a Hanford tank, where the imaging elbow would be inserted through the riser and its movement would be limited around that area. During the experiments, targets were measured with the camera being located at three different distances away from Panel A, i.e., 25’, 15’, and 7’, respectively; this is illustrated in Fig. 3 for Panel C.

There were altogether four different situations involved in data acquisition. The first situation was measurement of the nondescript targets on Panel A, where the regular FTP technique would be utilized. (Traditionally FTP has been utilized to characterize targets perpendicular to the camera axis.) The second was measurement of nondescript targets on Panels B and C, where the camera had to be tilted and the non-perpendicular FTP technique utilized. (A description of the non-perpendicular FTP technique is given below.) The third and the fourth cases were both for measurements of the “known” targets, where FTP may not be as applicable as the CCMS technique due to the known dimensions of the “known” targets. For both cases, a simple “pixel-counting” approach was utilized. For the third case, “known” targets on Panel A were measured. For the fourth case, “known” targets on Panels B and C were measured. Given that the camera had to be tilted for the fourth case, special care was needed to correct for distortions due to the skewed field of view [11].

PRINCIPLES OF FTP ANALYSIS OF NON-PERPENDICULAR TARGETS

FTP analysis of perpendicular targets (“regular FTP”) requires that the optical axis of the camera be perpendicular to the flat surface on which the target is placed. However, in practical situations, such as Hanford waste tank measurements, this perpendicular condition will not in general be met easily due to difficulties involved with limited optical access and imaging system delivery. For example to view a bottom area near the far edge of a 75’-diameter tank from a riser located at the other end of the tank, it is more practical to tilt the camera toward the far edge than to physically deliver the camera to a position directly above that area to satisfy the perpendicular condition.

To handle this non-perpendicular situation for images recorded with a tilted camera, a two-step approach has been developed. Referred to as “non-perpendicular FTP,” this approach assumes that there is a hypothetical flat surface at the position of the target. This hypothetical surface is perpendicular to the camera's optical axis and intersects with the actual surface on which the target lies (see hypothetical reference surface in Fig. 4). With this hypothetical surface as the reference surface, "regular FTP" is still applicable and is used to reconstruct the height profile of a target on located on the hypothetical reference surface (see Fig. 4). The second step of the non-perpendicular FTP analysis procedure is to treat the flat surface on which the target actually lies as a second "target" to be measured. Using "regular FTP," a second height profile is reconstructed, representing the true surface as a slope with regard to the hypothetical reference surface. By subtracting the second "slope" profile from the first "target on slope" profile, the height profile of the target of interest is obtained.

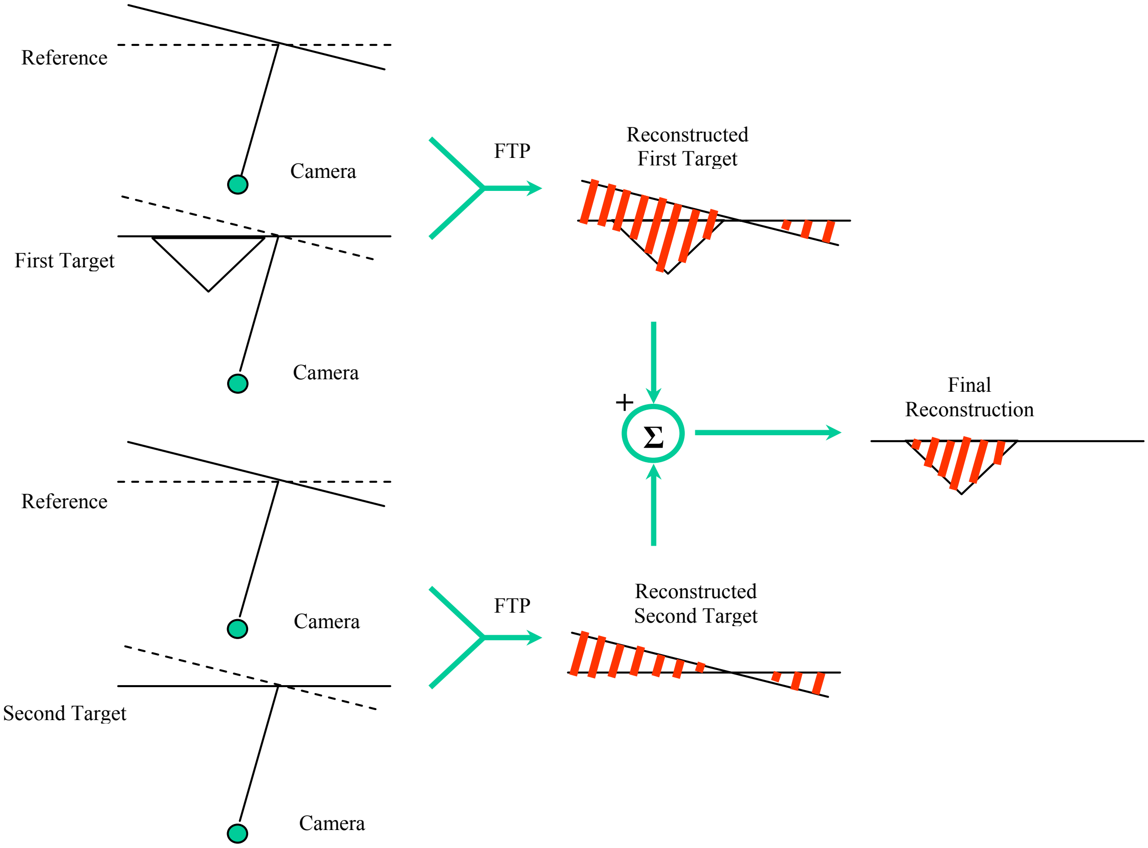

Figure 4. An illustration of the non-perpendicular FTP technique.

Of course since the height values generated so far are all with regard to the hypothetical reference surface rather than the actual surface the target actually lies on, this derived height profile presents a distorted profile of the target. Corrections are needed to convert the distorted profile into its original form. Another issue concerning corrections is that, since the camera is tilted rather than looking perpendicularly, images the camera acquires are geometrically distorted. The geometrical distortions are manifested on objects closer to camera (the left half of image in Fig. 4) appearing to be stretched, while objects farther away from the camera (the right half of image in Fig. 4) appearing to be condensed. These geometrical distortions need to be corrected as well. Equations have been derived to handle all these necessary corrections for the non-perpendicular FTP [11].

FTP DATA ACQUISITION FOR "KNOWN" TARGETS

For the pipe-shaped "known" targets, a straightforward "pixel counting" approach has been adopted since FTP is not as applicable as traditional imaging techniques that use geometry, images acquired at different distances, and the dimensions of known objects to estimate other volumes. The "known" targets involved in this stage of experimentation are all pipe-shaped objects. These targets are used to simulate hoses that might be found in Hanford waste tanks. For these targets, FTP is not applicable due to the sharp edges and shadows, which would cause significant discontinuities in the projected grid patterns. With the pixel counting approach, there is no need to project grid patterns on targets being measured. Only one image is needed for analysis, which should include the "known" targets and objects of known dimensions. In this case, the known objects are masking tape pasted on the panels, simulating weld joints of the bottom plates of the tank (see Fig. 3). Knowing that the "known" targets are cylinder pipes, their diameters and lengths (hence volumes) can be estimated by combing pixel counts and the length-per-pixel information derived from the known objects.

Similar to the FTP measurement of nondescript targets, there were also two different situations involving measurement of "known" targets. For targets are on Panel A, the camera was aimed perpendicular to the panel and targets. For targets are on Panel B or C, the camera had to be tilted to take images, where the non-perpendicular condition comes into play. Again, in this latter case, only one image was recorded for analysis. The image should contain nondescript targets to be measured, as well as some known objects for inference of the physical pixel size.

As was the case with non-perpendicular FTP, geometrical distortions are present in the target image due to the skewed FOV. An approach similar to that for the non-perpendicular FTP (described above) was utilized to correct the distortions [11]. To apply this approach, some important parameters are needed. These parameters are: the camera's tilt angle, the distance from the camera to the targets, and the FOV size of the camera at that distance. These were recorded during the data acquisition process.

FTP DATA ANALYSIS AND RESULTS

Given the four different situations involved in data acquisition, their associated data analysis approaches are also different. Specifically, FTP analysis of perpendicular targets ("regular FTP") was applied to images of nondescript targets that were perpendicular to the axis of the camera (Panel A); non-perpendicular FTP was applied to images of nondescript targets under the non-perpendicular condition pertaining for Panels B and C; direct pixel-counting was utilized for "known" targets on Panel A; and pixel-counting with geometrical correction was utilized for "known" targets on Panels B and C.

Table I. presents the results of the FTP analysis of the volume of the non-descript targets on Panels A, B, and C (Fig. 2). The true values of the non-descript targets were independently determined by traditional methods (by water displacement and by weight from density) employing multiple determinations to establish measurement uncertainties for the traditional methods. The FTP analysis was "blind," i.e., those performing the FTP analysis were not provided the true values until after completion of the FTP analysis. The volume of the non-descript targets were determined using images acquired at different distances. FTP does not require images from different distances; images were acquired at different distances to facilitate comparison with traditional imaging techniques that use geometry, images acquired at different distances, and the dimensions of known objects to estimate other volumes. With some exceptions, the most accurate FTP determinations were those made at the greatest distance. On average, FTP was able to determine the volume of the non-descript targets to within 5.7% of the true value. As described above, determination of the targets on Panels B and C required geometric corrections to correction for the non-perpendicular viewing configuration and hence the geometric skewing of the images; it should be noted that the FTP accuracy for non-perpendicular targets appears to be comparable to the accuracy for perpendicular non-descript targets. Also as noted above (p. 6), the heights of the nondescript targets were low to simulate piles of material left in a waste tank; the low height adds to the difficulty of accurately determining the volume.

Table I. FTP volume measurement results for non-descript targets. (Refer to Figure 2 for identification of targets.)

#	Panel	Target	Distance (feet)	Offset (feet)	Volume (cm^3)	True Value (cm^3)	Error	
							Absolute (cm^3)	Percentage (%)
1	B	S1	25	9	1093	1028±12	65	6.3
2	B	S1	15	9	1033	1028±12	5	0.5
3	A	S2	25	0	1069	1070±7	-1	-0.1
4	A	S2	15	0	1133	1070±7	63	5.9
5	A	S2	7	0	1120	1070±7	50	4.7
6	C	S3	25	18.5	1804	1954±10	-150	-7.7
7	C	S3	15	18.5	1719	1954±10	-235	-12.0
8	C	S4	25	18.5	1117	1071±6	46	4.3
9	C	S4	15	18.5	967	1071±6	-104	-9.7
10	A	S5	25	0	358	422±5	-64	-15.2
11	A	S5	15	0	447	422±5	25	5.9
12	A	S5	7	0	425	422±5	3	0.7
13	B	S6	25	9	665	647±4	18	2.8
14	B	S6	15	9	625	647±4	-22	3.4

ANALYSIS AND RESULTS OF “KNOWN” TARGETS

The “known” targets involved in this stage of experimentation are all pipe-shaped objects. These targets are used to simulate hoses that might be found in Hanford waste tanks. For these targets, FTP is not applicable due to the sharp edges and shadows, which would cause significant discontinuities in the projected grid patterns.

A simple pixel-counting approach has been developed to estimate volumes for these “known” targets. Assuming that these targets are cylinder pipes lying flat on the tank bottom, their volumes can easily derived if their diameters and lengths can be estimated. Given that the weld joints of the tank bottom plates are visible in the acquired images, the “weld joints” may be utilized as known objects from which the physical pixel size of the images can be inferred. With this pixel size information available, diameters and lengths of the pipes can be obtained by counting the number of pixels along the respective orientations on the images. The volume is then derived according to the standard equation for the volume of cylinders. It should be pointed out that this pixel counting approach only provides relatively rough estimates, since it assumes that the pipes lie flat on the tank bottom. If this is not the case, very likely the volumes will be underestimated.

For images acquired with the camera looking straight forward (perpendicularly) toward Panel A, the procedure for volume analysis with pixel counting is as follows. First, a target image is loaded. Using the IMAQ software line drawing tool, a straight line is drawn across a selected pipe's diameter to estimate the diameter by automatic pixel counting. Then the pixel area covered by the pipe in the image is outlined with the IMAQ ROI drawing tool in order to estimate the pipe length, again using automatic pixel counting. With this information, the program automatically calculates the volume for the pipe.

For "known" targets on Panels B or C, the pixel counting approach is still utilized for volume analysis. However, since the images are acquired with the camera tilted, there are geometrical distortions in the images due to the skewed FOV. These distortions have to be corrected before the pixel counting analysis can be applied. The equations utilized for correction in this case [11] are similar to the equations for non-perpendicular FTP. However, since no height profile is available in this case, the equations do not have the factors related to height values.

The procedure for analysis of this type of targets consists of two steps. The first step is to correct the distortions. The acquired images are loaded, the experimental parameters (such as the distance, tilt angle, and FOV width) are inserted into the program, and the distortions are removed by the correction program. Then the same procedure described above for pixel counting analysis is performed to estimate volumes for the "known" targets.

Table II contains the results of the volume determinations of the "known" targets using pixel counting techniques. On average, this pixel counting technique was able to determine the volume of the "known" targets to within 10.4% of the true value. Geometric correction for non-perpendicular viewing does not seem to affect the accuracy of pixel counting. Images were acquired at only one vertical distance (25 ft, 7.62 m). Perhaps if images were acquired at other distances, then combining the results of the two determinations might improve the accuracy of determining the volumes.

CONCLUSION

The Institute for Clean Energy Technology (ICET) at Mississippi State University has initiated a blind performance evaluation of the capability of Fourier transform profilometry (FTP) to determine the volume of targets under simulated waste tank conditions. This is a multi-stage evaluation with subsequent stages having greater similarity to conditions that pertain in Hanford waste tanks. To date, the first stage of this evaluation has been successfully concluded. On average, we are able to use FTP to determine volumes of non-descript targets to within 5.7% of their true values. All techniques have their strengths and limitations. FTP cannot accurately handle large height discontinuities and it cannot handle objects that are partially hidden or shaded. In order to determine the volumes of pipe-like "known" objects that cannot accurately

Table II. Volume measurement results for “known” targets using pixel counting. (See Fig. 2 for identification of targets.)

#	Panel	Target	Distance (feet)	Offset (feet)	Volume (cm^3)	True Value (cm^3)	Error	
							Absolute (cm^3)	Percentage (%)
1	A	B2	25	0	976	1086	-110	-10.1
2	A	P1	25	0	201	180	+21	+11.7
3	A	P2	25	0	821	721	+100	+13.9
4	A	H1	25	0	179	166	+13	+7.8
5	A	H3	25	0	574	497	+77	+15.5
6	B	B1	25	9	518	543	-25	-4.6
7	B	P1	25	9	204	180	+24	+11.8
8	B	P2	25	9	695	721	-26	-3.6
9	B	H2	25	9	374	331	+43	+13.0
10	B	H3	25	9	546	497	+49	+9.9
11	C	B3	25	18.5	1376	1629	-253	-15.5
12	C	P1	25	18.5	208	180	+28	+15.6
13	C	P2	25	18.5	764	721	+43	+6.0
14	C	H1	25	18.5	184	166	+18	+10.8
15	C	H2	25	18.5	353	331	+22	+6.6

be analyzed by FTP, a pixel counting technique (with geometric correction when appropriate) was developed. The pixel counting technique can determine the volume of “known” objects to within 10.4% of the true value on average.

Future stages of the FTP performance evaluation will include stitching the results of FTP volume determinations from single images together to obtain an overall volume determination, use of a curved (‘bowl-shape”) tank bottom rather than a flat tank bottom, and a simulated deployment at ICET prior to demonstration at Hanford’s Cold Test Facility.

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