DEVELOPMENT OF QUANTITATIVE IMAGING PROBES FOR *IN SITU* VOLUMETRIC DETERMINATION OF HANFORD TANK WASTES

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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 Diagnostic Instrumentation and Analysis Laboratory's (DIAL) efforts is to develop, fabricate, and deploy quantitative inspection tools for the Hanford waste tanks that will be remotely operable and that will provide quantitative information on the amount of wastes remaining. A collaborative arrangement has been established with the Hanford Site to develop probe-based inspection systems for deployment in the waste tanks.

DIAL's inspection approach is to independently and quantitatively estimate the amount of residual waste by using Fourier-transform profilometry (FTP) and stereovision. 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. DIAL 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 DIAL 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. Stereovision also provides 3-D determinations of depths/heights by combining images simultaneously recorded by two (or more) cameras from different viewpoints. Volumetric determinations by two independent methods will permit more accurate determination of the volume and the associated uncertainty.

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 a given waste tank and the chemical makeup of the residue. Mississippi State University’s Diagnostic Instrumentation and Analysis Laboratory’s (DIAL) 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.

DIAL’s inspection approach is to independently and quantitatively estimate the amount of residual waste by using Fourier-transform profilometry (FTP) and by using stereovision. These systems were developed by DIAL for inspection of an off-line Joule-heated melter at the West Valley Demonstration Project (5,6). 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. DIAL 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 DIAL 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. Stereovision also provides 3-D determinations of depths/heights by combining images simultaneously recorded by two (or more) cameras from different viewpoints. Volumetric determinations by two independent methods will permit more accurate determination of the volume and of the volume estimation uncertainty.

METHODS

Fourier Transform Profilometry

Fourier transform profilometry (FTP) is a non-contact, 3-D shape measurement technique (7). 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.

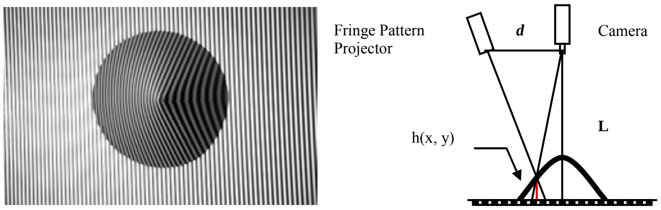

Fig. 1. Diagram illustrating the principle of Fourier-transform profilometry.

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

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

where ΔΦ (x, y) gives the phase modulation due to the object-height elevation, *h(x, y)*; *L* gives the distance from the camera aperture to the reference plane; *d* represents the distance between apertures of the projector and the camera; 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).

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

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* 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. In an experiment where *L* = 763 cm (~25ft), *d* = 100 cm, X_{pixel} = 512, the repeating frequency of fringe lines before projection was 300 lines per inch, a Kodak Carousel 4200 projector was used, and a camera lens with 150-mm focal lens was used, a resolution of 0.49 cm/pixel has been achieved. In the Hanford waste tanks, FTP observation distances will be in the range 3 m (10 ft) to 23 m (75 ft). Because the observation distance is longer, we are developing an improved optical system in order to obtain accurate volumetric determinations at these distances.

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 (8,9). The phase values generated from inverse Fourier transforms are all wrapped in the range of $-\pi$ 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.

Stereovision

Stereovision is an extensively developed branch of machine vision (10-13). It is widespread in a large range of scientific research and practical applications from space exploration, industrial inspection, robotics to remote sensing. Stereovision allows 3-D reconstruction by relying on the use of geometrical rules. It is based on the difference between two (or more) images of the object of interest recorded from different viewpoints. Finding the same points (or other features) in two images from different cameras so that the matched points are the same projections of a point in the scene is referred to as "matching." Stereoscopic computation involves three steps: first, calibration of the system to obtain the geometry of the two cameras versus a reference surface; second, creation of the disparity map, which is the most important step in application of stereovision. A disparity map is an image where the value of each pixel corresponds to the number of pixels one has to move left or right to find the corresponding pixel in the other image. Finally, the disparity map is used to obtain the 3-D reconstruction of the target surface. Application of stereovision to waste tank inspection provides 3-D topographic reconstruction of selected surfaces and permits an independent quantitative determination of the volume of residual materials. Furthermore, the 3-D reconstruction can be viewed on the computer from different user-selected perspectives.

APPLICATION

Successful deployment of the imaging systems into the hostile chemical and radiation environment of the Hanford waste tanks imposes unique requirements on a robotic manipulator platform. In addition to the obvious articulation and payload requirements, there are physical access constraints and operational features that must achieved. The target environment for the system is a large underground tank 23 m (75 ft) in diameter with a 15-m (50-ft) dome height and located 2 to 3 m (6 to 10 ft) below grade. Since the Hanford tanks typically have limited access through 10-cm (4") and 30-cm (12") diameter risers with the larger usually occupied by monitoring and retrieval equipment, it is advantageous that any inspection system be deployable through the smaller 10-cm diameter risers. It is also highly desirable that the inspection system be capable of deployment by two technicians with a minimum of facility infrastructure support.

The design of a manipulator that meets these objectives has been undertaken. The design utilizes a bare minimum number of members with forces and torques for articulation provided by actuators that are located external to the tank where possible. The manipulator system (Fig. 2) consists of the following: (i) a 4.5-m (15-ft) tall lightweight external tower that is mounted onto the flange of a tank riser, (ii) a rotational actuator that traverses vertically along the tower, (iii) a set of telescoping tubes, (iv) a tubular camera / illumination and projection housing at the bottom of the probe which is pivoted ± 135° via (v) an “elbow” joint. Raising and lowering of the probe along the tower traverse as well as the extension of the telescoping tube section is achieved using a motorized cable winch and pulley system. Similar pulley systems are used to manage the electrical cables for the camera/light projection module as well as the elbow actuator.

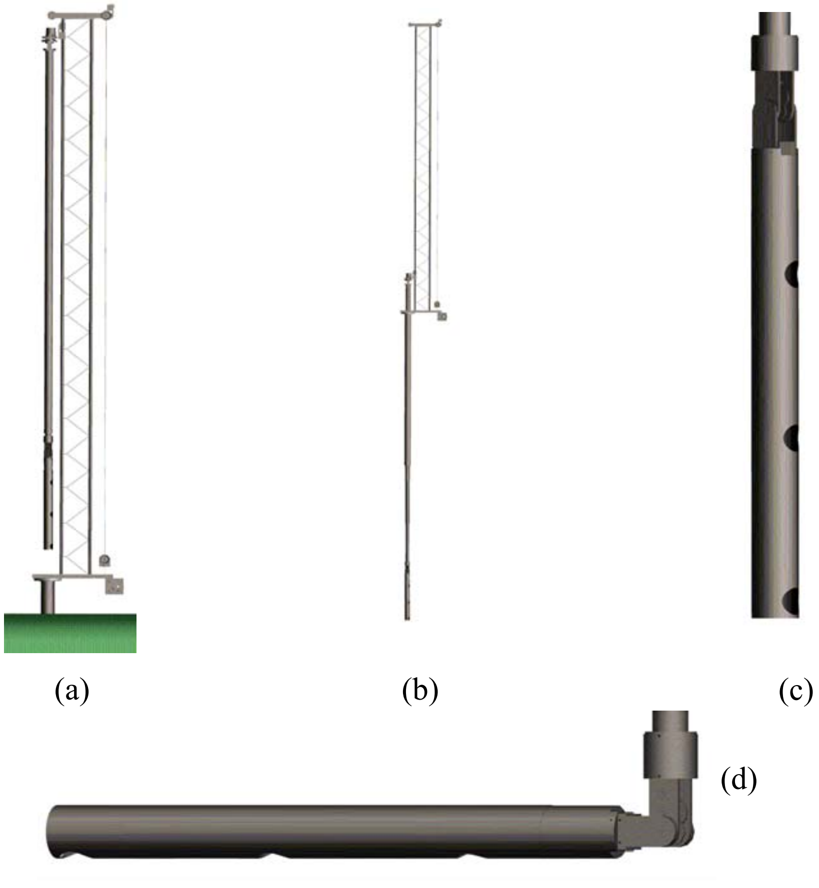

Fig. 2. DIAL imaging systems probe system. (a) Probe-based system mounted on tank riser. (b) Probe-based system showing configuration with probe inserted through riser into tank. (c) Close-up of instrument arm in the vertical position as it will be when inserted in tank. (d) Close-up of instrument arm rotated by 90° by elbow actuator to permit viewing of tank bottom.

The manipulator has three degrees of freedom along typical spherical coordinates, Z, Θ, and Φ with the Z-axis oriented along the tank riser, the Θ-axis movement provided by the rotation of the telescoping sections about the riser axis, and the Φ-axis movement provided by the articulated elbow. The maximum range of movement along these axes is Z=12 m (39 ft), Θ=360°, and Φ= ±135°. The arrangement of the camera and illumination optics within the camera module section utilizes turning mirrors to redirect the projected light and the camera field of view from and to the axis of the module housing. This is necessary to overcome packaging constraints and to provide the required separation distance between the projection axis and the camera field of view. Fig. 3 illustrates the design of the FTP module arm; the stereovision module arm contains two cameras. To facilitate erection by a maximum of two technicians, the probe system consists of sub-assemblies that weigh less than 20 kg (44 lbs) each with the entire system weighing less than 180 kg (400 lbs). Fig. 2(a) shows the manipulator and FTP system erected along the support tower and ready for deployment; Fig. 2(b) shows the manipulator fully extended into a tank; and Figs. 2(c) and 2(d) show the elbow joint in the straight position to view sides of tank and bent 90° to view tank bottom.

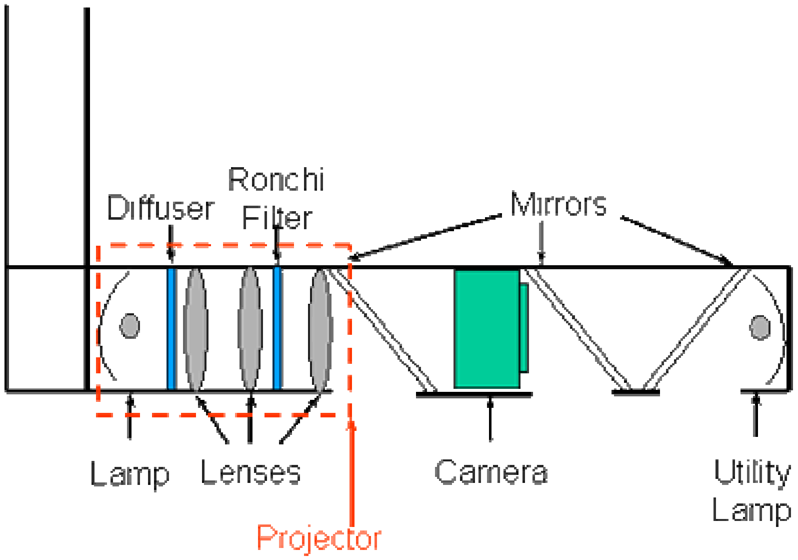

Fig. 3. FTP optics module that is attached at the elbow to the telescoping manipulator.

CURRENT STATUS

Current Status of the FTP System

Currently, a prototype FTP imaging system and the associated software packages for image acquisition and FTP analysis are being modified for waste tank inspection. With the aid of this prototype system, preliminary measurement experiments have been carried out under various simulated conditions. In all these measurements, the target was a right circular paper cone with the dimensions as shown in Table I. This target was measured under different experimental settings that would be typically found in practical situations. For each measurement, FTP analysis was performed and both the peak height and the volume of the cone were calculated on the basis of the analysis results. These height and volume values were then compared with the ground truth data to evaluate system performance.

Table II shows some typical experimental results and compares them with the ground truth data. For these results, the camera-to-target distance was set to 462.3 cm (~15'), 617.2 cm (~20'), and

828.3 cm (~27’), respectively. As observed in the table, as far as the peak height and the cone volume are concerned, the system performs very well in terms of the relative percentage errors. All errors for the peak height were within 1%, while errors for the volume were no more than 2%.

Table I. Dimensions of the right circular cone utilized as the target in FTP simulated measurements.

Base Diameter (cm)	**Peak Height (cm)**	**Volume (cm^3)**
26.70	10.40	1941.00

Table II. Results for FTP simulated measurement experiments. The percentage errors were calculated against the ground truth data provided in Table I.

Exp. #	**Camera-to-Target (L) (cm)**	**Camera-to-Projector (d) (cm)**	**Measured Peak Height (cm)**	**Error (%)**	**Measured Volume (cm^3)**	**Error (%)**
1	462.3	19.53	10.30	1.0	1904.48	1.9
2	617.2	19.37	10.39	0.1	1978.90	2.0
3	828.3	27.15	10.44	0.4	1960.11	1.0

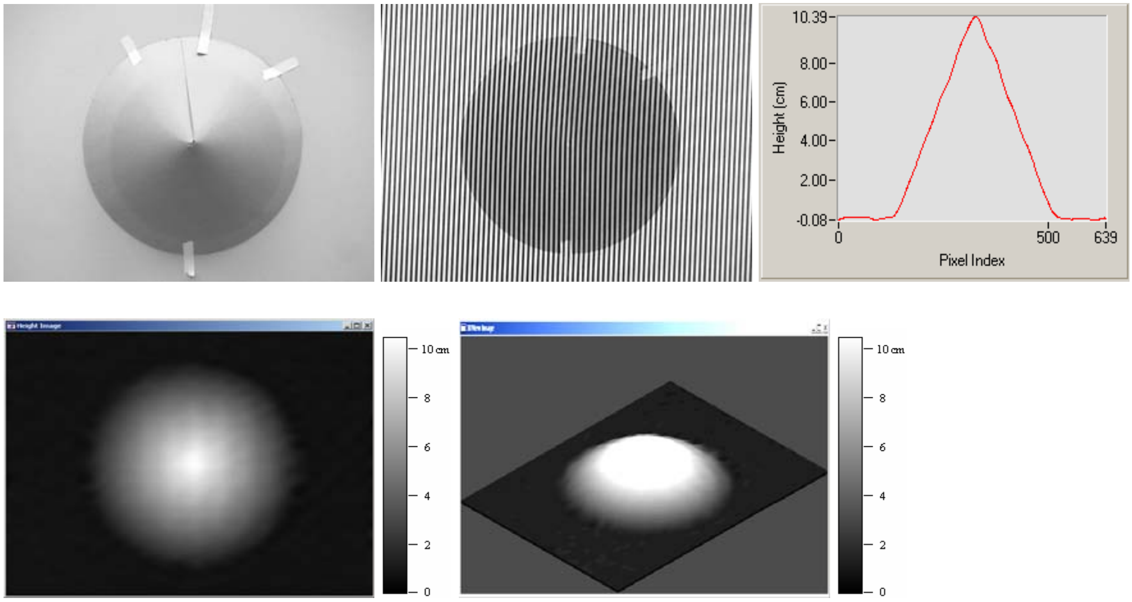

Fig. 4. Images of the original target and the reconstructed results for the measurement experiment #2 (in Table II) with L = 617.2 cm and d = 19.37 cm. In the top row from left to right are the original target, the target with projected fringe lines, and reconstructed 1-D profile along the horizontal cross section at the peak of the cone. In the bottom row on the left is the reconstructed 2-D profile of the cone, and on the right the reconstructed 3-D profile of the target.

To further illustrate the system performance, images of the original target and the recovered results are also presented in Fig. 4. As demonstrated with the images, all of the reconstructed results (in the form of one-dimensional, two-dimensional, and three-dimensional profiles) reproduced the geometrical shape of the original target with excellent fidelity. In addition to the numerical results, these images further verify the effectiveness of the developed FTP system for the quantitative inspection task under discussion.

Current Status of Stereovision System

The stereovision system that DIAL developed for off-line Joule-heated melter inspection (5,6) is being modified for deployment in the Hanford waste tanks. Application of stereovision to waste tank inspection permits an independent quantitative determination of the volume of residual materials in the tanks. For tank inspection, two shock-resistant, chemical- and radiation-protected, small Sony block cameras will be used to record high spatial resolution images from the instrument arm of a telescoping probe (Fig. 2). We have modified the block cameras for use in the robotic arm. Finding the same points (or other features) in two images from different cameras so that the matched points are the same projections of a point in the scene is referred to as "matching." This algorithm produces a reliable dense disparity map which will then be used to compute the 3-D positions of the scene points given the imaging geometry. Different techniques and approaches, including both epipolar and non-epipolar methods, have been evaluated to fit the tank inspection purpose. The epipolar method involves matching pixels along lines associated with camera motion, the epipolar lines. Non-epipolar methods remove explicit use of epipolar geometry, allowing direct use of multiple cameras with arbitrary geometries. One of the programs we are developing for fast stereo matching is based on the techniques reported by Sun (13). We have integrated an object-matching function into our stereovision system. This allows the operator to select and reconstruct the 3-D profile of a user-selected object in the viewing scenes. We have also developed software for 3-D surface reconstruction. The new program allows us to inspect the target surface from different viewing angles and provides a better visualization and measurement approach. Fig. 5 presents two 3-D reconstructions that we have obtained using the software we have developed; these compare well with the current state-of-the-art for stereovision (13).

We have also improved the camera control and image acquisition software for the two-camera stereovision system. The two cameras can now be independently controlled. Either camera can be used to monitor the target in video mode and can acquire images separately. We have integrated camera control for a single camera, image acquisition, and computing functions into a single software package. Subsequently we have incorporated a modified version of the camera-control software developed for the Fourier Transform Profilometry (FTP) effort into the stereovision software package.

The stereovision effort is currently investigating the effect on stereovision performance of different parameters, such as distance and angles between the cameras, working distance between cameras and objects of interest, window size for disparity map computation, etc. We have also investigated the possibility of utilizing Pulnix cameras rather than Sony block cameras. The Pulnix cameras were found to produce better quality images and hence better disparity maps. However, the Pulnix cameras do not have computer-controlled zoom capability (as the Sony block cameras do); for application in the Hanford waste tanks, the ability to zoom is expected to be essential. For other applications, the Pulnix cameras might be a better choice.

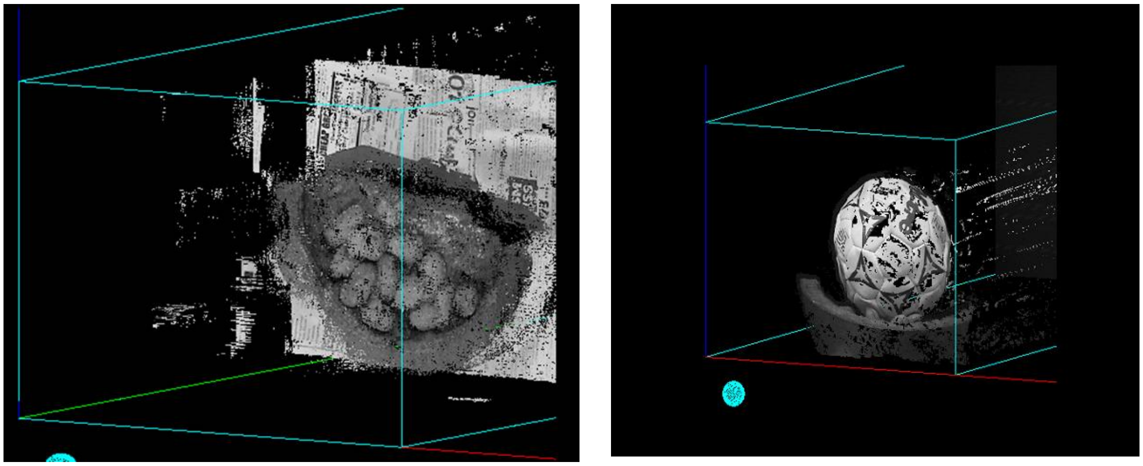

Fig. 5. Examples of 3-D reconstructions from stereovision images. The 3-D reconstruction on the left is of pelletized surrogate material in a graphite crucible that has been cut in half and all these objects set atop a newspaper. The 3-D reconstruction on the right is of a volley ball setting in a graphite crucible. The blue dots in both reconstructions permit the reconstructions to be viewed from different angles by rotating the reconstructions on the computer screen.

The stereovision system has acquired images at selected working distances [9 m (30 ft), 12 m (40 ft), 15 m (50 ft), 18 m (60 ft), and 21 m (70 ft)] appropriate to acquiring data in a Hanford waste tank. We are currently processing this data in order to determine the precision of the stereovision determinations as a function of distance. These measurements will be repeated with different camera separations in order to optimize the stereovision system for deployment in the Hanford waste tanks.

SUMMARY

In order to provide valuable information about the amount of residual materials and their chemical makeup, DIAL has formed a collaborative arrangement with the Hanford Site to develop probe-based inspection systems for deployment in Hanford waste tanks. The probe-based inspection systems that DIAL is developing and fabricating are (i) capable of being remotely operated; (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.

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