Surface scanning through a cylindrical tank of coupling fluid for clinical microwave breast imaging exams

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Purpose: Microwave tomographic image quality can be improved significantly with prior knowledge of the breast surface geometry. The authors have developed a novel laser scanning system capable of accurately recovering surface renderings of breast-shaped phantoms immersed within a cylindrical tank of coupling fluid which resides completely external to the tank (and the aqueous environment) and overcomes the challenges associated with the optical distortions caused by refraction from the air, tank wall, and liquid bath interfaces.

Methods: The scanner utilizes two laser line generators and a small CCD camera mounted concentrically on a rotating gantry about the microwave imaging tank. Various calibration methods were considered for optimizing the accuracy of the scanner in the presence of the optical distortions including traditional ray tracing and image registration approaches. In this paper, the authors describe the construction and operation of the laser scanner, compare the efficacy of several calibration methods—including analytical ray tracing and piecewise linear, polynomial, locally weighted mean, and thin-plate-spline (TPS) image registrations—and report outcomes from preliminary phantom experiments.

Results: The results show that errors in calibrating camera angles and position prevented analytical ray tracing from achieving submillimeter accuracy in the surface renderings obtained from our scanner configuration. Conversely, calibration by image registration reliably attained mean surface errors of less than 0.5 mm depending on the geometric complexity of the object scanned. While each of the image registration approaches outperformed the ray tracing strategy, the authors found global polynomial methods produced the best compromise between average surface error and scanner robustness.

Conclusions: The laser scanning system provides a fast and accurate method of three dimensional surface capture in the aqueous environment commonly found in microwave breast imaging. Optical distortions imposed by the imaging tank and coupling bath diminished the effectiveness of the ray tracing approach; however, calibration through image registration techniques reliably produced scans of submillimeter accuracy. Tests of the system with breast-shaped phantoms demonstrated the successful implementation of the scanner for the intended application. © 2012 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4711799>]

Key words: optical imaging, 3D scanning, microwave imaging

I. INTRODUCTION

Microwave imaging spectroscopy (MIS) exploits low level microwave signals to study the composition of dielectric materials. Ongoing studies at Dartmouth (Hanover, NH) have shown MIS to be an effective new imaging modality for noninvasive breast cancer detection and have resulted in the development of several prototype clinical imaging systems.^{1–3} The technique records microwave signals as they propagate through the breast and employs an iterative model-based algorithm to reconstruct dielectric property images of the tissue.^{4–6}

Determining surface geometry of the breast when placed in a liquid environment is a common problem in microwave imaging which has received little attention. Cameron *et al.*⁷ and Williams⁸ developed a submerged laser scanning system capable of detecting the distance between the breast surface and microwave radiators at a few points. Creation of a scan-

ning system with increased resolution that operates from outside of the tank is preferred because it simplifies the housing of electrical/electronic components and eliminates the possibility of introducing artifacts into the microwave data due to electromagnetic scattering from the device, itself. The scanning system developed here utilizes simple laser line projections and a CCD camera to capture the surface geometry of objects (e.g., the breast) within the tank with a high degree of resolution and accuracy. Furthermore, the system resides completely outside of the imaging tank and does not interfere with the acquisition of microwave data.

Several technologies have been developed to capture the surface of objects in underwater environments. Examples include acoustic measurement techniques for ocean bottom surveys and robot guidance;⁹ projected light patterns for Moiré topology;¹⁰ stereo photogrammetry;^{11,12} light stripe projection;¹³ and laser triangulation.¹⁴ However, many of these methods involve either imaging through a flat

transparent plate or submerging the imaging system in the aqueous environment. They can also suffer from low spatial resolution, need active light projection of complex patterns, or require easily registered object features or fiducial markers.

While multiple variations of laser scanning systems have been developed, difficulty arises when reconstructing objects placed in a liquid-filled cylindrical tank because the refraction of light at the boundaries of the tank walls (and the optical distortions caused by the intervening fluid) nonlinearly degrades the camera images. To overcome these limitations, Yamashita *et al.* developed a ray tracing algorithm for a point laser scanner with a cylindrical tank¹⁵ and for a laser line scanner with a rectangular tank.¹⁶ An alternative approach foregoes the camera model and ray tracing in favor of various image registration techniques. A grid of control points with known positions can be submerged in the tank and imaged with the camera. A transformation from image space to the real world locations of the control points can be found using one of the several registration methods [e.g., piecewise linear, polynomial, locally weighted mean, and thin-plate-spline (TPS) approaches].^{17–19} In the scanner embodiment described here, we compare the accuracy of a modified version of Yamashita's ray tracing algorithm with the image registration strategy. We then test the new implementation to acquire surface geometries within our existing MIS system. While the scanner design is specific to our particular imaging geometry, the approach is general and the results can be extended to other microwave imaging configurations or any other surface scanning application where the object of interest resides in (and the scanner is external to) an aqueous environment.

II. MICROWAVE BREAST EXAM

Our current MIS system is self-contained within an integrated clinical exam platform as shown in Fig. 1. The breast is suspended through an aperture in the surface of the exam table and immersed in an aqueous glycerin solution that improves the coupling of the microwave exposure to the breast by minimizing the electromagnetic property discontinuity at the breast–fluid interface. While other coupling fluids, for example, canola oil, have been used success-

fully,^{20,21} glycerin when mixed with water is attractive because the liquid also effectively attenuates undesired surface waves and unwanted reflections of the microwave fields from the breast surface and tank walls. Meaney *et al.* have previously described the use of an aqueous glycerin bath for microwave imaging²² and its attenuating effect on surface wave multipath signals.²³ A circular array of monopole antennas is positioned concentrically around the breast with each antenna sequentially acting as a transmitter while the remaining members of the array record the tissue response to these transmissions. To acquire cross-sectional planes of data, the antennas are retracted in unison from a starting position near the top of the tank. Our conformal imaging technique requires the spatial definition of two zones within the imaging plane—the target region (breast tissue) and the surrounding homogeneous background (glycerin bath).¹ Li *et al.* have shown that resolution within the target region increases dramatically as the defined imaging zone boundary approaches the actual breast surface.²⁴ The improvement is partially due to the increase in unknown image property parameters that can be deployed in the target region (i.e., within the breast) since the properties of the surrounding background (i.e., glycerin bath) are already known. When image reconstructions are performed on a circular mesh encompassing both the breast tissue and the bath (i.e., when the location of the breast within the antenna array is unknown), the algorithm tends to blur the images by overly smoothing the property change across the breast boundary. Massa *et al.* have developed adaptive meshing strategies^{25–27} that deploy a higher percentage of the limited number of (image reconstruction) unknowns to zones of high property variation. Conformal mesh methods perform a similar function by distributing all of the degrees-of-freedom within the target (breast) region.^{28–30}

III. SCANNER DESIGN

The surface scanning system consists of two low-power LED laser line generators and a machine vision CCD camera mounted on a rotating gantry. This assembly is positioned concentrically around the MIS imaging tank as shown in Fig. 2. The lasers are oriented to have their projections normal to the tank wall, eliminating refraction of the laser beam illuminations. To capture the surface geometry within the

FIG. 1. Photograph of the clinical MIS breast exam platform and imaging aperture (left) with the bed top removed revealing the imaging tank and microwave antenna array (right).

FIG. 2. Photograph of the laser scanner mounted on a circular gantry attached to imaging tank base.

tank, the laser lines are swept across the entire surface of the object of interest. The camera and lasers were designed to rotate around the center of the imaging tank in a mathematically equivalent configuration to rotating the object in front of the laser–camera pair (common of many laser scanners).

Several of the parameters affecting the optical distortions observed by the camera are determined by the MIS system design. Specifically, the imaging tank, made of acrylic glass, has an inner radius of 140 mm and a wall thickness of 12.7 mm. The aqueous bath is 80% glycerin by weight. The concentration of the bath determines its index of refraction; for instance, an 80% glycerin solution produces an index of refraction of 1.44.³¹ Other parameters are defined by the laser scanner, itself. These include the intrinsic (focal length, principal point, and skew) and extrinsic (position relative to the center of the tank and rotation about the three camera axes) camera parameters.

In constructing the laser scanner, the position, resolution, and focal length of the camera were determined. The radial position of the camera was governed by physical constraints and was mounted on a rotating, 270 mm radius, circular gantry (Fig. 2). Given the radial distance of the camera from the center of the tank, a Point Grey Flea[®] 2 1.4 megapixel color machine vision package was selected for both its small size and high resolution. The active area of the CCD is a 1392×1032 array of $4.65 \mu\text{m}$ square pixels. For this radial distance and sensor size, a 6 mm focal length lens captured the entire width of the tank within the camera's field-of-view (FOV).

The angle between the lasers and camera, Γ , influences the resolution and imaging capabilities of the scanner. However, as Γ increases, object features can hide portions of the

laser line from the camera's FOV. To mitigate this problem, a second laser line was added on the opposite side of the camera to provide an alternate view of the surface geometry. We determined that a camera angle of 45° was optimal by considering the effects of the laser angle on the output error, the depth of field, the resolution, and the ability to capture the laser intersection with an object of interest in the FOV. This angle allowed us to recover surfaces that were not perfectly uniform while still maintaining depth of field and resolution.

Scans are initiated through custom software and a GUI. A stepper motor with an optical encoder rotates the gantry 360° around the imaging tank and electronically triggers the camera to acquire images at known positions. Figure 3 shows a photograph of the optical scanner integrated with the imaging tank containing a breast phantom. The CCD camera was fitted with a Bayer color filter for acquiring images. The two lasers, one red and one green, operate at 635 and 532 nm wavelengths, respectively. To extract the lines from the acquired images, bilinear interpolation was applied independently to each color plane. A weighted average of the product of pixel location and intensity was taken across each row of pixels to find the center of the laser line within the row with subpixel accuracy. These image coordinates were then used to calculate the surface geometry by implementing the calibration algorithms described in Sec. IV.

IV. CALIBRATION ALGORITHMS

IV.A. Analytical ray tracing

The algorithm developed by Yamashita *et al.*¹⁵ takes a point on the image plane and traces the ray of light creating that point from the camera, through the tank wall, to its intersection with the object's surface using a virtual pinhole camera model. Simple vector algebra is combined with Snell's law of refraction to account for optical distortion at the outer and inner walls of the tank. By calibrating the position of the

FIG. 3. Photograph of the prototype scanner consisting of a machine vision camera and laser line generators on a circular gantry driven by a stepper motor.

camera relative to the laser and the center of the tank, the location of the surface point can be calculated.

We extended the same approach of using a virtual pinhole camera model to trace the ray of light as it propagates through the series of index of refraction changes associated with the air, tank walls, and coupling fluid. To convert a pixel coordinate (u, v) in the camera image plane to the unit vector $[X' Y' Z']$ of the ray of light intersecting that point, the transformation

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_u & \alpha & c_u \\ 0 & f_v & c_v \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} \quad (1)$$

is inverted where the intrinsic camera parameters—focal length (f_u and f_v components), skew (α), and principle point coordinates (c_u and c_v)—are embedded.³²

Three coordinate systems are involved (1) the image coordinate system (ICS), (2) the camera coordinate system (CCS), and (3) the world coordinate system (WCS). ICS (u, v) is two dimensional with horizontal (u) and vertical (v) components, where the origin is defined as the top left corner of the image with positive u extending to the right and positive v extending down. WCS (x, y, z) is fixed in space with its origin at the top center of the imaging tank and the z -axis oriented colinearly with the vertical dimension of the tank. CCS (x', y', z') has its origin at the camera focal point and its x' and y' axes parallel to the image plane, which creates a left-handed coordinate system whose position and orientation move with the camera as it rotates around the tank. The position and orientation of the camera are described by extrinsic camera parameters—rotation about the principal axes of the CCS and translation from the WCS origin. The intrinsic and extrinsic camera parameters were calculated in a one-time, two-step process based on a Camera Calibration Toolbox for MATLAB using a series of images of a black and white checkerboard pattern of $1 \text{ cm} \times 1 \text{ cm}$.³²

Once the system was calibrated, points on the image plane were traced to points on the object's surface using a simplified version of Yamashita's algorithm in which a normalized ray emanating from the camera center was found using the pinhole camera model. The ray was intersected with the cylinder defining the outer wall of the tank by solving Eqs. (2)–(4). Specifically, point p on a ray containing locations a and b is described by

$$p = (b - a) * t + a. \quad (2)$$

Similarly, points on a cylinder are defined by

$$\|(p - c) \times d\|^2 = r^2, \quad (3)$$

where c is a point on the cylinder axis, d is the normalized direction of the cylinder axis, and r is the radius. Combining Eqs. (2) and (3) and solving for t yields the length of the ray from point a to its intersection with the cylinder

$$\|[(b - a) * t + a] - c\| \times d\|^2 = r^2. \quad (4)$$

Once t is known, p can be found from Eq. (2). Snell's law of refraction

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1} \quad (5)$$

is then applied at the point of intersection to find the ray of light traveling through the tank wall where θ_1 is the angle between the incoming ray and the normal to the cylinder at the point of intersection, θ_2 is the similar angle for the outgoing ray, and n_1 and n_2 are the indices of refraction of the starting and intersected media, respectively. The ray also intersects with the inner wall of the tank and Snell's law is used accordingly to identify the ray traveling through the glycerin bath.

This ray intersects the plane defined by the laser line generator, which creates a series of points on the object's surface that can be described by

$$(p - o) \cdot n = 0, \quad (6)$$

where o is a point on the plane and n is the unit normal vector of the plane. Combining Eq. (6) with Eq. (2) and solving for t yields

$$t = \frac{(o - a) \cdot n}{(b - a) \cdot n}. \quad (7)$$

Again once t is known, Eq. (2) is solved to find the point of intersection with the plane. As the laser plane rotates about the object, a point cloud defining the surface contour is generated.

IV.B. Polynomial registration

In this study, we used second and third order bivariate polynomials of the form $a \cdot x^n \cdot y^m$ fit to the control point pairs using a least squares approximation for image registration^{17,33,34} where the n th order polynomial is given by

$$T(x, y) = \sum_{j=0}^n \sum_{k=0}^j A_{jk} x^j y^{j-k}. \quad (8)$$

For N control point pairs $[(x_i, y_i)$ in the moving image and (X_i, Y_i) in the fixed image], the coefficients A_{jk} can be found from a least squares fit by solving the system of linear equations

$$\begin{bmatrix} A_{00} \\ A_{10} \\ A_{11} \\ \vdots \\ A_{nn} \end{bmatrix} = \begin{bmatrix} 1 & x_1^1 y_1^0 & x_1^0 y_1^1 & \cdots & x_1^n y_1^n \\ 1 & x_2^1 y_2^0 & x_2^0 y_2^1 & \cdots & x_2^n y_2^n \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_N^1 y_N^0 & x_N^0 y_N^1 & \cdots & x_N^n y_N^n \end{bmatrix}^{-1} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_N \end{bmatrix}. \quad (9)$$

For N greater than n , the pseudoinverse was used to find the least squares approximation.

IV.C. Piecewise linear registration

Piecewise linear image registration methods were first described by Goshtasby.³⁵ In this technique, control points in the fixed image are triangulated (most commonly using a Delaunay method) and matched to corresponding points and triangles in the moving image. These transformations have the advantage of detecting local distortions often missed by global methods—as long as the regions are small with

respect to the geometric scale of the deformations. Each triangle pair contains three control point pairs (x_i, y_i) and (X_i, Y_i) which are combined to create new point sets of the form (x_i, y_i, X_i) and (x_i, y_i, Y_i) . Linear transformations that map the triangles onto each other are found by determining the planes that pass through the new three dimensional points

$$A_0 + A_1x + A_2y + A_3z = 0, \quad (10)$$

where the coefficients are given by the determinants

$$A_0 = \begin{vmatrix} 1 & y_1 & z_1 \\ 1 & y_2 & z_2 \\ 1 & y_3 & z_3 \end{vmatrix}; \quad A_1 = \begin{vmatrix} x_1 & 1 & z_1 \\ x_2 & 1 & z_2 \\ x_3 & 1 & z_3 \end{vmatrix};$$

$$A_2 = \begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix}; \quad A_3 = - \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{vmatrix}, \quad (11)$$

with z_i replaced by X_i or Y_i to find the respective transformation for each coordinate in the fixed image.

IV.D. Local weighted mean registration

The local weighted mean (LWM) method attempts to combine the benefits of the previous two approaches—merging the smooth nature of polynomials with the local sensitivity of piecewise functions—by fitting an N th order polynomial to each control point and its $N - 1$ nearest control point neighbors. The value at any point (x, y) is then the weighted mean of the polynomials passing over that point,³³ with the image transformation $T(x, y)$ given by

$$T(x, y) = \frac{\sum_i W_i \cdot P_i(x, y)}{\sum_i W_i}, \quad (12)$$

where $P_i(x, y)$ is the polynomial corresponding to the i th control point and W_i is a weight related to the distance between the point of interest (x, y) and the i th control point.

IV.E. Thin-plate-spline registration

The use of bivariate splines, such as thin-plate-splines, for image registration has been described and refined by many investigators including Goshtasby,³⁶ Zagorchev,³⁴ Glasbey,¹⁸ and others.^{37–39} This registration method models the transformation as a deformation of a thin plate of infinite extent where mechanical loads of varying intensity and direction are applied and centered at each of the control points. A stiffness or smoothing parameter is often utilized to control the amount of deformation caused by the loads. In this study, the smoothing (or approximating) thin-plate-spline is defined as

$$T(x, y) = A_0 + A_1x + A_2y + \sum_i B_i r_i^2 \ln r_i^2 \quad (13)$$

was used where r_i^2 is the Euclidean distance to the i th control point and the coefficients A_i and B_i are chosen to minimize

$$p \sum_i E_i(T) + (1 - p) \iint_{-\infty}^{\infty} \left\{ \left(\frac{\partial^2 T}{\partial x^2} \right)^2 + \left(\frac{\partial^2 T}{\partial x \partial y} \right)^2 + \left(\frac{\partial^2 T}{\partial y^2} \right)^2 \right\} dx dy. \quad (14)$$

TABLE I. Ray tracing algorithm input parameters and their expected values.

Input parameter	Description	Expected/calibrated value
Γ	Camera rotation about Y'	45°
θ	Camera rotation about X'	15°
ϕ	Camera rotation about Z'	0°
$[x_o, y_o, z_o]$	Camera position in RWC	$[190, 190, 0]$ mm
R_i	Inner tank radius	139.7 mm
R_o	Outer tank radius	152.4 mm
N	Index of refraction of bath	1.44
$[f_x, f_y]$	Focal length in X' and Y'	$[6.00, 6.00]$ mm
$[p_u, p_v]$	Principal point coordinate	$[696, 516]$
$\tan(\alpha)$	CCD skew	0

Here, E_i is the Euclidean norm of $T(x_i, y_i)$ to its corresponding control point (X_i, Y_i) and p denotes a smoothing parameter that varies from 0 to 1 and determines the stiffness of the spline where values close to 1 result in an interpolating spline (least squares fit) and values close to 0 lead to complete smoothing (and approximation) at the control points.

V. RESULTS

Scanner development and testing was performed in two stages. First, the accuracy of the calibration algorithms described in Sec. IV was analyzed based on a grid of known dimensions. In the case of the ray tracing algorithm, a sensitivity analysis was performed to determine sources of error in the scanner design. Then, the fully assembled scanner was evaluated using analytical and breast-shaped phantoms.

V.A. Sensitivity analysis of ray tracing

Given the numerous inputs to the ray tracing algorithm and their nonlinear relationships, numerical experiments were performed to determine the tolerances on each variable required to maintain an output (surface scan) accuracy of 1 mm. During the sensitivity analysis, each input was individually perturbed from its expected (calibrated) value listed in Table I to estimate its effect on the overall output error.

Fig. 4. Mean and maximum algorithm output error due to errors in the input rotation angles of the camera: Γ (rotation about Y' -axis), θ (pitch about X' -axis), and ϕ (roll about Z' -axis). Linear least squares fit lines added.

TABLE II. Results of parameter sensitivity analysis. Linear regression coefficients for mean and maximum errors due to positive and negative perturbations of each input parameter.

			Mean error		Maximum error	
Parameter		Units	Negative perturbation	Positive perturbation	Negative perturbation	Positive perturbation
Camera rotation angles	Γ	mm/deg	−4.6640	4.6514	−6.4425	6.4321
	θ		−4.0016	3.9990	−5.6300	5.6093
	Φ		−1.1944	1.1941	−2.3616	2.3619
Camera position	$(X^2 + Y^2)^{1/2}$	mm/mm	−0.3576	0.3577	−0.8961	0.8964
	X		−0.7123	0.7100	−1.0882	1.0813
	Y		−0.9262	0.9248	−2.0116	2.0139
Refractive index	N	mm/index	−0.0382	0.0380	−0.1398	0.1387
Tank radius	(R_i, R_o)	mm/mm	−0.1375	0.1367	−0.4565	0.4511
	R_i		−0.0069	0.0068	−0.0210	0.0206
	R_o		−0.1444	0.1435	−0.4766	0.4708
Camera focal length	(f_u, f_v)	mm/pixel	−0.0514	0.0508	−0.1450	0.1427
	f_u		−0.0318	0.0314	−0.0838	0.0828
	f_v		−0.0340	0.0336	−0.0805	0.0794
Principal point	p_u	mm/pixel	−0.2064	0.2067	−0.2968	0.2967
	p_v		−0.1688	0.1687	−0.2223	0.2220
Skew	$\tan(\alpha)$	mm/ $\tan(\alpha)$	−0.0054	0.0054	−0.0138	0.0138

Experimental and ground-truth data were generated from a 13×15 black and white checker board grid (with 10 mm squares, see Fig. 5) submerged in the imaging tank coplanar with one of the planes defined by the laser line generators. The algorithm was executed with perturbed input variable values to determine their effects on the calculated output coordinates. Each input variable perturbation produced a series of residual vectors associated with the output error for the grid point locations and we computed the maximum and mean errors in each case.

Figure 4 shows the mean and maximum output errors from perturbing the camera rotation angles about their presumed positions which have approximately linear relationships with small deviations in these input variables. In addition to the three camera rotation angles, we perturbed

horizontal camera location, tank dimensions, coupling fluid concentration, and the intrinsic camera parameters. Camera dislocations involved translation of the camera in space with respect to the origin of the WCS. Here, we exploited the symmetry of the problem and only evaluated errors due to translations in the x – y plane (the tank is cylindrical and coaxial with the z -axis so translation in the z -direction only produced concomitant output offsets). The acrylic glass tank used in the MIS system has manufacturing tolerances in both the outer radius and wall thickness of ± 1.65 and ± 1.14 mm, respectively. The concentration of the aqueous glycerin bath provides another source of input error as it directly influences the fluid's index of refraction.³¹ Linear trends similar to those observed in Fig. 4 were found for these other input parameters; accordingly, we report the perturbation sensitivity

FIG. 5. Photograph of the test grid as seen through the scanner's CCD camera. Red crosses mark grid points that were extracted and the green circles denote the control points used for registration (red crosses without green circles were used as evaluation points).

FIG. 6. Residual error vectors denoting the difference between actual grid point coordinates and their calculated positions (e.g., using the ray tracing algorithm). Blue arrows illustrate residuals of the evaluation points, whereas red arrows illustrate residuals of the control points used for registration.

TABLE III. Results of imaging method comparisons. All values are given in millimeters.

Method	Test point residuals			Control point residuals			Mean residual
	Mean	Standard deviation	Maximum	Mean	Standard deviation	Maximum	
Ray trace	1.8595	0.9686	4.739	1.8679	0.9520	4.5541	1.8637
Polynomial ($n = 3$)	0.1191	0.0774	0.4006	0.1114	0.0807	0.4063	0.1152
Polynomial ($n = 4$)	0.1051	0.0802	0.4780	0.0840	0.0798	0.4125	0.0946
Piecewise linear	0.2129	0.1740	1.2315	0.0000	0.0000	0.0000	0.1065
LWM	0.1126	0.0792	0.4679	0.0624	0.0551	0.2920	0.0875
TPS	0.3036	0.3377	2.1245	0.2865	0.2698	1.2122	0.2950

for each variable as the slope of the linear regression to the maximum and mean errors (the intercept was zero in all cases) in Table II.

Table II indicates that uncertainties in the camera rotation angles and position were the greatest sources of error in the ray tracing algorithm. The other parameters can be calibrated well within the tolerances needed to produce a surface output error of 1 mm. Unfortunately, even small errors in Γ (on the order of 0.5°) yielded output errors exceeding 1 mm. Similarly, the camera position must be calibrated to within 0.5 mm to produce an output error on the order of 1 mm.

V.B. Registration method comparison

To determine the accuracy of each registration algorithm described in Sec. III, the same calibration grid of known point coordinates was used. In this case, once the grid was imaged, the corners of each checkerboard square were extracted and these points were divided into two uniformly sampled groups across the grid. The first group contained control points for the various registration methods. The second group contained evaluation points. Figure 5 depicts the submerged grid as seen through the CCD camera where the red crosses indicate the extracted points and green circles denote locations designated as control points for registration.

For each registration method, the control points were used to determine a transformation from image space to real world coordinates of the grid. The transformation was then applied to both evaluation and control points (evaluated separately) to determine the accuracy of the transformation. For

each point, the Euclidean distance from the calculated position to the actual location was found. Figure 6 shows these residuals as vectors from each point's actual to calculated position, respectively. The direction of the residuals varies due to the small nonlinear aberrations in the camera lens and the distortions caused by the imaging tank; however, for sufficiently small magnitude errors, the direction is relatively inconsequential. The maximum, mean, and standard deviation of the residual distances are reported in Table III. For each method, the mean residual distance of the combined point sets is also calculated. All of the image registration techniques provided better results than the analytical ray tracing method (as noted in Sec. V.A, sensitivity to camera angle and position errors make calibration of these quantities extremely critical and we were not able to adequately control these input variables). While the LWM method produced the lowest average residual error, it had difficulty applying the transformation to points outside of the calibration grid space (e.g., near the top of the imaging tank). The global polynomial methods demonstrated the best compromise between average error and robustness.

FIG. 7. Point cloud of a breast phantom generated by the prototype scanner. The dark blue dots represent data from the red laser and the light green dots data from the green laser.

FIG. 8. Deviation of the surface mesh of the scanned cone-shaped phantom (shaded) from the phantom's actual physical dimensions (semi-transparent). All units are in millimeters.

FIG. 9. Deviation of the surface mesh produced by red laser data from the surface mesh produced by green laser data. All units are in millimeters.

V.C. Phantom experiments

As a more complete evaluation of scanner accuracy, the prototype system was used to image both analytical and breast-shaped phantoms submerged in the imaging tank. The polynomial registration algorithm was chosen to calculate the surface coordinates from the scanner images. A geometric cone was machined to precise dimensions from synthetic materials. Breast phantoms were also constructed by segmenting breast MRI scans acquired with a prototype MIS-in-MR system (in which a smaller version of the microwave imaging tank was introduced into the bore of the MR scanner and the breast was positioned in the imaging array similarly to its placement in the breast coil system during prone clinical exams).⁴⁰ These images provided volumetric data on the natural deformation of the breast due to its buoyancy in the glycerin bath. 3D computer models were created from the segmented volumes and the physical phantoms were produced on a 3D printer.

FIG. 10. Deviation of the surface mesh of the scanned breast-shaped phantom (shaded) from its actual physical dimensions (semi-transparent). All units are in millimeters.

TABLE IV. Results of phantom experiments. All values are given in millimeters.

Surface mesh comparison	Mean error	Standard deviation	Maximum error
Cone: scan to phantom	-0.3852	0.1182	0.7640
Cone: red scan to green scan	-0.2671	0.4769	14.6054
Breast: scan to phantom	0.5475	0.3164	1.6824

A typical point cloud generated by the scanner is shown in Fig. 7. The red dots represent data from the red laser and the green dots show data from the green laser. From this point cloud, a triangular boundary mesh of the surface geometry was extracted with a marching cubes algorithm. This mesh was then compared to the one used to generate the phantom. The accuracy of the scanner was quantified as the distance from each node of the scanner mesh to the surface of the phantom mesh. Figure 8 illustrates this comparison for the conical phantom (average error was 0.385 mm). Figure 9 shows the deviation of a mesh produced from the red laser data relative to the one generated from the green laser data (average error was 0.267 mm). Finally, Fig. 10 compares the corresponding surfaces from a breast-shaped phantom (average error was 0.547 mm). The modest increases in scanner error relative to the calibration target results are primarily attributed to the difficulty in precisely positioning the phantoms within the tank to a fraction of a millimeter. Overall, however, the phantom experiments demonstrate the ability of the scanner to accurately find the surface geometry with submillimeter accuracy. Table IV summarizes the results from these experiments. The maximum error in Table IV (~ 15 mm) comparing the surface meshes generated from the red laser data with the green laser data results from poor angular view of the laser lines with the camera at the top edge of the cone and nicely illustrates the advantage of using two laser line generators positioned differently relative to the camera (which reduced the error to <1 mm relative to the actual cone phantom surface when the surfaces from both lines of data were used).

VI. CONCLUSION

We have designed and implemented a laser scanning system capable of recovering object surfaces when placed in a cylindrical transparent tank filled with an optically clear fluid for application in microwave imaging of the breast. The system represents a relatively fast and accurate method of three dimensional surface capture that resides entirely outside of and separate from the tank. In this paper, we evaluated two strategies for calculating the object's surface coordinates from the scanner image data—(1) the traditional machine vision approach based on pinhole camera calibration and triangulation of light rays to reconstruct the object surface and (2) calibration based on image registration between homologous points identified in a known target and its acquired images. Optical distortions imposed by the MIS imaging tank and coupling bath diminished the effectiveness of the ray tracing approach. Specifically, sensitivity analysis of the

ray tracing equations—which included index of refraction changes between air, the plastic tank walls, and the intervening tank fluid—showed that errors introduced by camera rotation angles and global position are difficult to calibrate or control with sufficient accuracy to maintain an object surface scanning error of less than 1 mm. Calibration through image registration techniques proved more accurate and reliable and was able to produce scanned surface errors of 0.5 mm or less depending on the complexity of the object geometry.

Accuracy experiments, including studies of breast-shaped phantoms, demonstrated successful implementation of the scanner for the intended application with a remote scanning fidelity which is better than 1 mm when performed through the combined transparent tank and fluid environment. While the scanner has direct application to acquiring the surface geometry of a patient's breast when submerged in a coupling fluid during microwave imaging, it could easily be adapted to scanning the surfaces of submerged objects in other clinical and/or industrial settings where the scanning system, itself, is located outside of the aqueous environment.

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