Haptic Simulator for Training in Clinical Breast Examination

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2. Statement of Project Goals

Breast cancer among women has reached epidemic proportions in the United States; with current estimates indicating that one woman in eight will develop breast cancer during her lifetime [1]. Breast cancer is also the second leading cause of death for all women. It is estimated that approximately 40,200 women in the U.S. will die from the disease in 2003 [2]. The incidence rate of invasive breast cancer in white women increased by 1.1% each year from 1992 to 1998, most of which was seen in women ages 50-74. The incidence rate in African-American women stayed level during the same period, but some increase was seen among African-American women older than 50. From 1992 to 1998, breast cancer was the most commonly diagnosed form of cancer in women [3-5].

The vast majority (70-95%) of breast tumors are located by the woman herself [6], who in turn will seek confirmation of her findings from her primary health care provider. Although mammography has arguably reduced the breast cancer burden over the last two decades, approximately 17% of cancers appear between screenings [7]. Moreover, mammography has been reported to carry a number of risks, such as false-positive findings, radiation exposure, inconvenience, pain, economic burden, and anxiety [8-15]. In a recent and hotly debated study, Gotzsche and Olsen [15] reported that their review and evaluation of eight randomized mammography trials showed that in none of the trials did mammographic screening decrease overall mortality, although it did lead to more unnecessary surgeries. Miller et al. [16] concluded that in women aged 50-59 years, adding annual mammographic screening to clinical breast examination has no additional impact in reducing mortality from breast cancer.

Although the Department of Health and Human Services continues to recommend mammographic screening for women in their 40s and above, given the sporadic availability of mammography in rural and undeveloped regions, and considering the possible risks and limitations of mammographic screening, clinical breast exam (hereafter CBE) is now regarded as a method that can be very useful as part of a woman’s total breast health regimen [17-22].

However, training in clinical breast examination in most medical schools is cursory at best. CBE is a complex psychomotor skill. Health care providers need to learn to use a systematic pattern to ensure full coverage of breast tissue as well as the tissue near the collarbones and into the axilla.□ Most learn these skills from pamphlets and videotapes. Programs aimed at improving effectiveness of CBE have typically used silicone gel models with lumps of varying size. The models are short-lived under active use due to deterioration from the oil in human fingers. They achieve coverage of a variety of lump sizes and locations by deploying up to nine lumps in a single pair of breasts, which seriously compromises the representation of the relation of the lump to its neighboring tissue. Feedback is limited: presence or absence and size are the only parameters.□Further, the issue of false positives is not addressed in a systematic way. When clinicians fail to find lumps, there is no way to determine what skills were lacking, so coaching is based on gross motor movement suggestions.

At IMSC we are implementing a multimodal training system for clinical breast examination which permits self-paced learning. A haptic device tracks the hand and finger movements of the user as she/he explores a deformable elastic model of the breast and axilla on the computer screen. The haptic device, a 6DOF PHANToM, communicates forces back to the trainee's fingers that are like those that would be experienced in a similar "real world" examination. The user's hand is represented in the workspace of the digital breast as a three-fingered hand model, so that the final force and torque feedback can be calculated according to the "collisions" between the three fingers and the breast model. The system will include a database of breast models with wide coverage of sizes and shapes of breasts, location and size of tumors, relationship of the lump to neighboring tissue, and tissue density. Models can be retrieved from the database and explored at leisure; feedback can be provided at every step, including successful location of lumps and "detection" of lumps where none exist. The user's exploration path can be captured and compared to an expert's. Significant deviation into unproductive areas can be gently corrected with prompts from an intelligent coaching agent or "guidebot" as well as from the haptic device itself. Text-to-speech generation and synthesis will complement and supplement the information provided by the haptic system.□In a "tutorial review" mode, the system can take initiative in explaining specific details of the touch experience being currently rendered (using the haptic output). Spatial context information (i.e., the specific region of the breast currently in focus) is provided to the system by the haptic input. On the other hand, in an "exploratory" mode, the user can take initiative and make a verbal inquiry, such as "have I already explored this area?" All dialog between the user and the system is logged and available for online or post-hoc analysis. Computer vision techniques which capture user facial expression and gestures are combined with haptics and speech to monitor user state (e.g., user frustration) and trigger appropriate interventions as needed. Breast models can be explored in three ways: free exploration (no guidance), guided exploration (force feedback is applied to the user's fingertip to reinforce the correct path) and remote collaborative guided exploration ("hand over hand"), where the tip of the user's PHANToM can be captured and guided by a user at another location.

3. Project Role in Support of IMSC Strategic Plan

The project represents an opportunity to combine much of the basic technology that IMSC researchers have developed during the past several years to launch a significant initiative in the area of medical informatics. These include: 1) techniques for creating three-dimensional models including modeling from images, e.g. MRI images of breast tissue and physically-based animation, emphasizing deformable models of soft organs for real-time simulation [23-25]; 2) estimation-theory based methods for detecting the contact between the haptic probe (the virtual hand or fingertip) and the virtual object (in this case, the breast model) [26-28]; 3) novel low-level force-control algorithms for communicating touch sensations to the user like those encountered if the object is touched in the "real world." (Our supervisory hybrid control algorithms can be used to adapt to the current muscle dynamics and cognitive state of a particular user [29]); 4) techniques for haptic data compression and evaluation of the perceptual impact of compression of haptically rendered breast models [30]; 5) strategies for the description, storage, and retrieval of haptic data [31,32]. We can capture the finger movements of an experienced clinician during a breast exam and "play it back," so that a novice can retrace the exploratory path, with realistic touch sensation; further, we can calculate the correlation between the two paths and determine if they differ sufficiently to warrant further training; 6) techniques for the storage and retrieval of multiple streams of continuous media that preserve both inter- and intra-channel time dependencies [33]; 7) speech recognition and synthesis and integration of spoken and haptic input and output [34,35].

Development of the CBE application is informed at the basic research level by IMSC's Communication Vision. Of particular interest is using the application to examine the problem of multimodal sensing and fusion of data streams from speech, haptics, and vision during acquisition of complex skills. In particular we are interested in finding optimal ways of combining raw sensory input to do user state sensing (e.g., emotions) and detect and forestall user errors or otherwise make appropriate adjustments during problematic situations (for example, we can predict the user's trajectory using Kalman filters and nip unproductive paths in the bud), and also adjust system feedback to a level that best meets the needs of the individual user.

4. Discussion of Methodology Used

Detecting and Correcting User Errors during Training

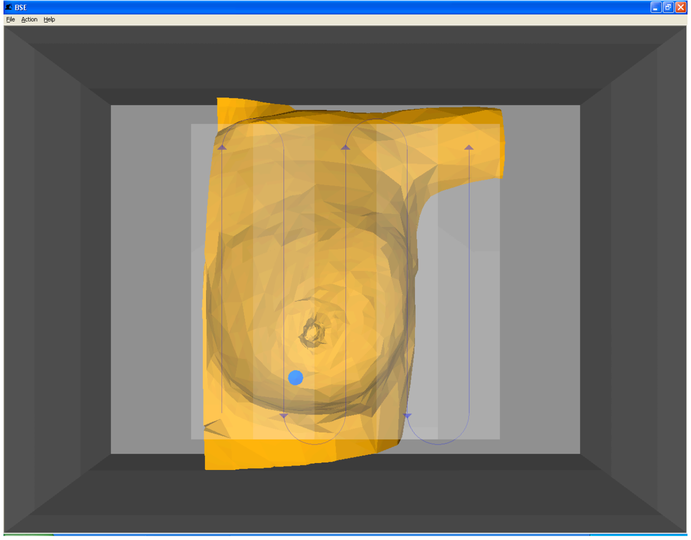

Figure 1. PHANToM workspace with breast model. Lawnmowever vertical stripe search pattern is superimposed on model.

The haptic device employed by the user in the CBE training task is the 6 DOF PHANToM from Sensable Technologies. The PHANToM provides force feedback in three translational degrees of freedom (the *x*, *y* and *z* coordinates of spatial location), and it provides torque feedback (pitch, roll and yaw) in three rotational degrees of freedom. The PHANToM outputs force and torque by calculating the collisions between the PHANToM tip or probe and objects in the virtual environment. Since our probe is represented in the virtual environment by a three-fingered hand model, the torque feedback can be calculated according to the collisions between the three finger tips and the virtual breast. For example, if there is only one collision detected between the left/right finger and the object, the user can feel force and a right/left turn torque. If all three fingers collide with the object, the user will only feel the force. This stream of haptic data during a user session is captured at 10ms intervals, time-stamped, and written to a log file. Thus we can say about a user for a given point in time the absolute location of his or her PHANToM probe, its location relative to the breast/axilla model, the force which is being applied, and the turning or twisting force at the users' wrist. From this basic data additional measures can be derived, including translation magnitude between consecutive readings [36], indices over arbitrary intervals, such as the users' trajectory or rate of acceleration, and summary indicators, such as mean force, maximum force, minimum force, and force variability [37].

Of the cues described above, we may classify some as explicit or intentionally produced by the user in service of task attainment (assuming that the user is conscientious and rule-following in the context of the training protocol), and some as implicit indicators of user state. That is, we assume that the user is able, after some practice, to form an intention to place the PHANToM probe at a specific location on the breast model, at a particular rotational orientation, with a particular use of force, and make adjustments thereto as appropriate.

The exploration pattern recommended for clinical breast examination consists largely in the users' pushing into the breast model with the PHANToM stylus at three successively greater levels of depth (shallow, medium, and deep), following a circular pattern roughly the size of a dime at each level, and then moving the stylus along the *y* axis to the next locus of palpation. The boundaries of the critical areas of the breast model relative to the previous location of palpation can be specified quite precisely, as can the degree of force required for the user to push into the model at the appropriate depth, and it will be possible to recognize the users' actions as intended to situate the haptic probe properly with respect to locus and depth of palpation, following a prescribed temporal ordering. Similarly it will be possible to recognize the users' attempt to follow a circular pattern of pressing at each successive level. And finally, it will be a simple matter to recognize the users' effort to move the probe the prescribed distance up the vertical stripe pattern to the next locus of palpation. The sections below describe how user errors are detected from the haptic data stream.

Vertical stripe errors. In our application, we erect vertical boundaries superimposed on the breast model. At any time, the user is constrained to exploring the "stripe" between two successive boundaries. We also provide a small degree of overlap between successive stripes so that the user does not feel too restricted. Small "windows" are embedded within these boundaries at their vertical extremities; these permit the user to move to the next stripe only after completely exploring the current stripe, thus enforcing the recommended pattern in CBE. If the user tries to move from one stripe to another without having completely explored the area (i.e., the user is not in the vicinity of the "windows" defined earlier), then this condition is detected and the system can, if desired, apply force feedback to the PHANToM device, preventing the user from straying off the vertical stripe pattern.

Circular pattern errors. In addition to following the vertical stripe pattern, the user must also execute a series of dime-sized circular palpations three times in a given location, each time increasing the level of force applied. In order to determine whether the user is following a circular pattern, we use the following algorithm:

1. Collect a few (say 10) coordinate data points using GHOST SDK functions. Discard the z-coordinate since only x and y information determines the circular path.
2. Compute the center of the "circle" as $x_c = \frac{1}{n}\sum_{i=1}^{n} x_i$ $\qquad$ $y_c = \frac{1}{n}\sum_{i=1}^{n} y_i$
3. Compute the radius of the "circle" as

$$\frac{Avg\left[\max\left\{EuclideanDist\left((x_i, y_i), (x_j, y_j)\right)\right\}\right]}{2} \qquad 1 \le i, j \le n$$

During this computation, we may, to improve performance, discard two or three coordinate pairs that are too "far off," essentially a filtering operation.

4. The average distortion of the points with respect to the computed circle can be determined by the mean of the Euclidean distance from the individual sample points to the nearest locations on the circle. The nearest points on the circle are determined by formulating the equations lines that pass through the sample points and the center of the circle. The equations are solved to determine the intersection points of the lines with the circle. These intersection points are closest to the corresponding sample points.

5. The average distortion computed in step (4) can be used to determine whether the user is following a circular path or not. If this parameter is above some empirically determined threshold, we conclude that the user is not following a circular path and vice-versa.

6. The circle center information from step (2) tells us the approximate region within a stripe that the user is currently exploring. Based on previous location information, we can determine whether the user is moving from one region to the next correctly, or is stuck in an area, or is jumping a large distance from one region to another. Appropriate action can be taken based on this information.

7. The radius information from step (3) indicates the size of the circular path. If the user is not moving roughly in a dime-sized path (10-15mm radius), we can prompt the user to do so.

Three-level force (palpation depth) errors. The user is required to explore each dime-sized region three times, the first time with slight force, the second time with moderate force and the third time with large force. To enforce this requirement, we employ a rudimentary finite state machine with three states, one for each level of force. The GHOST SDK allows us to sample the reaction force exerted on the PHANToM stylus by any object in the haptic scene graph. We sample the force during every graphics update event, and average it out for the duration of coverage of one dime-sized palpation. Based on empirical data, we then compute average force thresholds to classify the palpation as low force, medium force and large force. These decisions are used to determine transitions for the finite state machine. The only valid transition for this machine is a left-to-right progression; if this does not occur, the user can be prompted with an appropriate message.

Creation of Breast Models

In the computer graphics area, a great deal of research has been done on deformable and elastic objects. However, most of the methods require considerable computational time and are not suitable for producing real-time force feedback as users probe a three-dimensional model. In papers by IMSC colleague Mathieu Desbrun and collaborators [23.24.25], a space and time adaptive method is presented to simulate the animation of elastic objects and calculate force feedback. According to the method, the body of an object is partitioned into different resolution levels of tetrahedron meshes, and the local resolution is selected during the simulation based on the degree of deformation. Then, an adaptive Green strain tensor formulation is used to calculate the force feedback and deformation.

The current version of the GHOST SDK for the PHANToM does not support touching elastic models. Our first goal is to make a touchable elastic breast model for the PHANToM. To achieve this goal, we will use Desbrun's method. To date, we have created a closed-surface breast model (Figure 1) by 3D Studio Max. Its triangular meshes were used to generate different resolution levels of tetrahedral meshes by using a 3D Delaunay tetrahedral mesh generator [38]. Currently, using Desbrun's code for IRIX, we are abstracting the applicable parts (i.e., collision detection, deformation algorithm) to make a software package on Windows NT for the PHANToM to touch simple elastic objects like cubes and spheres and then apply the results to the breast model. We then propose to begin work on generating breast models from breast MR images, improving the 3D meshes, making a touchable breast model with different tissues inside and applying it in the CBE training system. Our collaborating radiologist has also provided us with a set of cranio-caudal and medio-lateral oblique mammography images which have been informing the work of model development

5. Short Description of Achievements in Previous Years

During the previous reporting year we: 1) conducted a comprehensive review of relevant literature in sociology of women's health care, biomedical palpation devices, and breast cancer screening strategies; (2) recruited an interdisciplinary team of researchers and advisory panel from IMSC, Norris Cancer Hospital, USC School of Nursing, USC Division of Preventive Medicine, John Wayne Cancer Center, and Los Angeles Children's Hospital; 3) participated in a proposal for funding to the National Cancer Institute under the umbrella of a proposal for a Center for Excellence in Cancer Communication Research, to be created at USC; and 4) secured permission to do preliminary trials of the system at a downtown Los Angeles clinic.

5a. Detail of Accomplishments during the Past Year

Since the last report we have (a) recruited new members to our interdisciplinary team, including Dr. Linda Hovanessian of the Department of Radiology at USC's School of Medicine, who has supplied us with sets of mammography images; (2) made substantial progress on the development of a generalized elastic breast model which can be touched with the PHANToM under the GHOST environment for Windows NT; (3) created an interface for exploration of breast models with the 6 DOF PHANToM; (4) developed new algorithms for using guided force feedback to correct user errors and reinforce productive user exploration patterns in the CBE training system; (5) completed a proposal to NSF for a multi-year project, "Inferring Problematic Events in User-Machine Interaction by Integrating Explicit and Implicit Multimodal Cues."

6. Other Relevant Work Being Conducted and How this Project is Different

With respect to our work beyond the level of this particular application, looking at the larger picture of the CBE system as an exemplar of how engineering science can be informed by social science, in particular theories of human communication, we would follow Chai et al. [39] and argue that most current research programs on multimodal interfaces have suffered from a neglect of the *context* in which user inputs are embedded, focusing rather narrowly on algorithms for multimodal fusion. In attempting to use cues from multiple modalities to infer user state it is necessary to consider the contexts in which the cues are situated. These might range from a dynamic context such as the evolving history of conversation with machine agents to fixed, system-level conditions. With respect to the latter, the user might be engaged in interaction with a simulated other (e.g., an agent), an actual other (e.g., a remote expert or trainer), or with the machine alone with neither parasocial nor human exchange. We anticipate that our interpretation of the mix of multimodal cues susceptible of capture will vary as a function of the training paradigm, that is, they will vary along a continuum of user display from largely *expressive* in the stand-alone training scenario, to more *conventional* in the presence of an agent, to more rhetorical or *social* when the user is guided by a remote expert or trainer [40,41], although we believe that the differences may be largely of degree rather than kind.

By an *expressive* display we refer to a cluster of observable user behaviors which have no apparent communicative purpose but rather serve to discharge tension, express pleasure or frustration, or otherwise allow the user to self-adjust in order to maximize comfort. Buck and vanLear refer to behavior of this type as "spontaneous," noting that it is non-propositional in content and that it is not independent of the user's underlying psychological or physiological state [42]. With vigilant self-monitoring, however, some expressive cues, particularly facial affect display, can be controlled or even faked in order to meet current conventional or social goals. By a *conventional* user presentation we imply that the user's primary goal is the unambiguous communication of her internal state, wants, needs, and goals, especially with respect to the task at hand, and that the behaviors exhibited will be conventional, rule-following, frequently iconic, and above all *consistent* across sensory display modalities. By a rhetorical or *social* user display we imply that in addition to instrumental or task-related needs the user's verbal and nonverbal behavior is directed to satisfaction of face-preservation and interpersonal needs (e.g., to appear competent; to win liking from the human trainer) and thus may contain both propositional and relational content, may be divorced from the user's underlying physiological and psychological states, and may be unintentionally or even strategically inconsistent across sensory modalities.

In the presence (or implied presence) of a human trainer, particularly when two-way communication is enabled, much of the user's emitted behavior that is not clearly directed at task accomplishment can be seen to be organized around *social* goals, which can range from face-saving in the presence of one's egregious training errors to overt efforts to engage the trainer in renegotiation of the training regimen. When social goals are present the task of detecting the user state becomes exponentially more complex. In the most straightforward case the mere presence of a human trainer may increase the richness of communication and hence the range and complexity of the cues displayed, and simple additive models of how cues combine may not be adequate. Cues in one modality which supplement or modify cues in another may be comparatively more distant temporally when there is a degree of design to the user's communicative display. In some cases cues may co-occur temporally but seemingly conflict with one another. For example, there may be more cue "leakage" as indicators of arousal states manifest themselves in leg or arm activity even while the user is making a conscious effort to control her facial affect display. There may be deliberate ambiguity: for example, the user's language may be polite and non-intense and he may deny having difficulty, but a "pseudo-spontaneous" [42] frown, grimace, or falling intonation pattern conveys his frustration and, suitably interpreted, could procure a desired intervention from the agent without the user's having to ask for it. Such inconsistencies among cues require special handling from an intention recognizer, yet most modality integration is biased towards speech and privileges the spoken input under the assumption that a nonverbal cue which is temporally connected to a verbal one is of like valence [39].

It seems reasonable to assume that users interacting with an agent will take pains to make a consistent display of their current needs and goals across modalities, on the grounds that it is necessary to be especially clear when communicating with a machine agent. And presumably the limitations of the agent's knowledge, response vocabulary and ability to recognize user intent function to constrain the range of cues displayed by human interactants. However, given the ample evidence that users view computers as social actors [43-45], the task of modeling the implicit cues in stand-alone or agent-assisted systems may be only slightly less difficult as users employ patterns of human social conduct and role relations as a template for interacting with machines.

In addition to being distinct from many other multimodal training applications, our project differs from other haptics-focused applications in medical informatics in that few are aimed at screening or diagnostic applications and not many are truly scalable. Most medical applications of haptics are targeted at tele-surgery and very few are aimed at diagnosis or screening [46.47.48.49]. Among the projects dealing with diagnosis a much smaller subset is related to palpation (two-finger diagnosis). Perhaps the most significant project related to palpation haptics is one at the State University of New York at Buffalo [46], where major effort is aimed at building a sensory system (a pressure transducer) that is connected to the physician's fingertips via a sensorized glove to collect real-time data on force and location during examination of a patient, and then replay the data later for a trainee who receives it passively through a haptic thimble. We believe our approach is far more scalable in that it is projected upon development of a database of breast images from a large repository of existing MRI slices rather than painstaking collection of data from patients in the individual physician's office. Further, our approach allows the trainee to actively participate in palpation as well as follow the path of an expert. Finally, our palpation strategy will featured a three-fingered hand model which will allow the user to feel torque about the simulated tumor mass.

7. Plan for the Next Year

During the next reporting year we expect to: complete the basic elastic breast model; create additional models incorporating data from MRI/mammography images, refine the user interface; integrate speech and haptics so that the user can control placement of the haptic stylus with voice and the user's placement of the haptic stylus triggers spoken system feedback when problematic situations are encountered; incorporate vision so that facial affect and body gesture cues can be incorporated into multimodal user state sensing along with speech and haptics; and conduct preliminary heuristic evaluation. We are also currently talking with groups from the neurosurgery and plastic surgery units at the USC School of Medicine on additional possible applications areas for simulation and training.

8. Expected Milestones and Deliverables

Development of Trainee-Machine System (TMS). A Database of basic breast models with variation in lump size and location along with software for querying the database. Create recognition algorithms for user errors from haptics. Provide haptic guidance and correction of user errors and integration of speech/haptic input/output systems. Begin laboratory trials of TMS.

Deliverables will include a database of breast models and software and tools for querying the database. The entire software package including the database of models could also be ported onto portable media for efficient distribution or could be made available over the Internet at little or no cost.

9. Member Company Benefits

The proposed project has the potential to attract new partners to IMSC including leaders in the medical simulation industry like Immersion Corporation, as well as potential member companies in medical informatics and visualization. Although the project is currently targeted towards clinician education it is clearly equally appropriate to training women in remote or rural areas without adequate clinical or mammography resources to perform breast self-examination, and thus would present an additional opportunity for technology transfer and commercialization.

10. References

[1] National Breast Cancer Foundation, "Early Detection," http://www.nationalbreastcancer.org/early_detection, 2003.

[2] American Cancer Society, "ACS Cancer Facts and Figures 2003 Released," http://www.cancer.org/docroot/NWS/content/NWS_1_1x_ACS_Cancer_Facts__Figures_2003_Released.asp, 2003

[3] U.S. Cancer Statistics Working Group, "United States Cancer Statistics: 1999 Incidence," Atlanta, Georgia, Department of Health and Human Services, Centers for Disease Control and Prevention and National Cancer Institute, http://www.cdc.gov/cancer/npcr/npcrpdfs/USCSreport.pdf, 2002.

[4] H. L. Howe, P. Wingo, M. J. Thun, et al., "Annual Report to the Nation on the Status of Cancer 1973 through 1998, Featuring Cancers with Recent Increasing Trends," *Journal of the National Cancer Institute*, vol. 93(11), pp. 824-842, 2001.

[5] R. T. Greenlee, M. B. Hill-Harmon, T. Murray, and M. Thun, "Cancer Statistics, 2001," *CA: A Cancer Journal for Clinicians*, vol. 51, pp. 15-36, 2001.

[6] S. Leight, P. Deiriggi, D. Hursh, D., Miller, and V. Leight, "The Effect of Structured Training on Breast Self-Examination Search Behaviors as Measured by Biomedical Instrumentation, *Nursing Research,* vol. 49 (5), pp. 283-289, 2000.

[7] I. Andersson, K. Aspegren, L. Janzon, T. Landberg, K. Lindholm, F. Linell, O. Ljungberg, J. Ranstam, and B. Sigfusson, "Mammographic Screening and Mortality from Breast Cancer: The Malmö Mammographic Screening Trial," *British Medical Journal*, vol. 297 (6654), pp. 943-948, 1988.

[8] S. A. Feig and R. E. Hendrick, "Radiation Risk from Screening Mammography of Women Aged 40-49 Years," *Journal of the National Cancer Institute Monograph*, vol. 22, pp. 119-124, 1997.

[9] B. K. Rimer and L. G. Blaumen, "The Psychosocial Consequences of Mammography," *Journal of the National Cancer Institute Monograph*, vol. 22, pp. 131-138, 1997.

[10] R. Harris, "Variation of Benefits and Harms of Breast Cancer Screening with Age," *Journal of the National Cancer Institute Monograph*, vol. 22, pp. 139-43, 1997.

[11] K. Kerlikowske and J. Barclay, "Outcomes of Modern Screening Mammography," *Journal of the National Cancer Institute Monograph*, vol 22, pp. 105-111, 1997.

[12] V. L. Ernster and J. Barclay, "Increase in Ductal Carcinoma *in situ* (DCIS) of the Breast in Relation to Mammography: A Dilemma," *Journal of the National Cancer Institute Monograph*, vol. 22, pp. 151-56, 1997.

[13] J. G. Elmore, M. B. Barton, V. Moceri, S. Polk, P. J. Arena, and S. W. Fletcher, "Ten-Year Risk of False Positive Screening Mammograms and Clinical Breast Examinations," *New England Journal of Medicine*, vol. 338, pp. 1089-1096, 1998.

[14] D. A. Berry, "Benefits and Risks of Screening Mammography for Women in their Forties: A Statistical Appraisal," *Journal of the National Cancer Institute*, vol. 90(19), pp. 1431-1439, 1998.

[15] O. Olsen and P. Gotzsche, "Cochrane Review on Screening for Breast Cancer with Mammography," *The Lancet*, vol. 358, pp. 1340-1342, 2001.

[16] A. B. Miller, et al.,"Canadian National Breast Screening Study-2: 13-Year Results of a Randomized Trial in Women aged 50-59 years," *Journal of the National Cancer Institute*, vol. 92(18), pp. 1490-1499, 2000.

[17] R. B. Burns, K. Freund, and A. S. Ash, "As Mammography Use Increases, Are Some Providers Omitting Clinical Breast Examination?" *Archives of Internal Medicine*, vol. 156, pp. 741-744, 1996.

[18] H. S. Pennypacker, L. Naylor, A. A. Sander, and M. K. Goldstein, "Why Can't We Do Better Breast Examination?," *Nurse Practitioner Forum*, vol. 10(2), pp. 122-128, 1999.
[19] M. B. Barton, R. Harris, and S. Fletcher, "Does This Patient Have Breast Cancer? The Screening Clinical Breast Examination: Should It Be Done? How?," *Journal of the American Medical Association*, vol. 282(13), pp. 1270-1280, 1999.
[20] C. J. Baines and A. B. Miller, "Mammography Versus Clinical Examination of the Breasts," *Journal of the National Cancer Institute Monograph*, vol. 22, pp. 125-129, 1997.
[21] I. Mittra, I., "Breast Screening: The Case for Physical Examination without Mammography," *Lancet*, vol. 343, pp. 342-344, 1994.
[22] J. K. Bobo, N. C. Lee, and S. F. Thames, "Findings from 752081 Clinical Breast Examinations Reported to a National Screening Program from 1995 through 1998," *Journal of the National Cancer Institute*, vol. 92(12), pp. 971-976, 2000.
[23] G. Debunne, M. Desbrun, A. H. Barr, and M. Cani, "Dynamic Real-Time Deformations using Space and Time Adaptive Sampling," in *Proceedings of ACM SIGGRAPH '01,* 2001.
[24] G. Debunne, M. Desbrun, M. Cani, and A. H. Barr, "Adaptive Simulation of Soft Bodies in Real-time," in *Computer Animation 2000*, 2000.
[25] G. Debunne, M. Desbrun, A. H. Barr, and M. Cani, "Interactive Multiresolution Animation of Deformable Models," in *Eurographics Workshop on Computer Animation and Simulation '99*, 1999.
[26] M. McLaughlin, G. Sukhatme, J. Hespanha, C. Shahabi, and A. Ortega, "Touch in Immersive Environments," Proceedings *of the EVA 2000 Conference on Electronic Imaging and the Visual Arts*, 2000.
[27] S. Roumeliotis, G. Sukhatme, and G. Bekey, "Circumventing Dynamic Modeling: Evaluation of the Error-state Kalman Filter Applied to Mobile Robot Localization" *Proceedings of the 1999 IEEE International Conference on Robotics and Automation*, 1999.
[28] M. L. McLaughlin, J. P. Hespanha, and G. Sukhatme, *Touch in Virtual Environments: Haptics and the Design of Interactive Systems*, IMSC Series in Multimedia, Prentice Hall, Saddle River, NJ, 2002.
[29] J. P. Hespanha and S. Morse, "Supervisory Control of Integral-input-to-state Stabilizing Controllers," paper presented at the 1999 European Controls Conference, 1999.
[30] A. Ortega, "Haptic Data Compression," in M. McLaughlin, J. Hespanha, and G. Sukhatme (Eds.), *Touch in Virtual Environments*: *Haptics and the Design of Interactive Systems*, Prentice Hall, Saddle River, NJ, 2002.
[31] C. Shahabi, A. Ghoting, L. Kaghazian, M. L. McLaughlin, and G. Shanbhag, "Analysis of Haptic Data for Sign Language Recognition," in *Proceedings of the First International Conference on Universal Access in Human-Computer Interaction (UAHCI)*, Lawrence Erlbaum, Hillsdale, NJ, 2001.
[32] C. Shahabi, M. Kolahdouzan, G. Barish, R. Zimmermann, D. Yao, and L. Fu, "Alternative Techniques for the Efficient Acquisition of Haptic Data," paper presented at ACM SIGMETRICS/ Performance 2001, Cambridge, MA. 2001.
[33] R. Zimmermann, M. Kolahdouzan, and C. Shahabi, "MASAA: A Casestudy in Building a Distributed Integrated Media Database," paper presented at the 33rd Hawaii International Conference on System Sciences (HICSS-33 '99), Maui, Hawaii, 2000.
[34] S. Narayanan, G. di Fabbrizio, C. Kamm, J. Hubbell, B. Buntschuh, P. Ruscitti, P., and J. Wright, "Effects of Dialog Initiative and Multi-modal Presentation Strategies on Large Directory Information Access," *Proceedings of ICSLP* (pp. 636-639), 2000.

[35] G. Di Fabbrizio, S. Narayanan, and P. Ruscitti, “Unifying Conversational Multimedia Interfaces for Accessing Network Services across Communication Devices,” Proceedings *of IEEE Multimedia Expo,* vol. *22*(4), pp. 1-4, 2000.

[36] C. S. Hundtofte, G. D. Hager, and A. M. Okamura, “Building a Task Language for Segmentation and Recognition of User Input to Cooperative Manipulation Systems,” *Proceedings of the 10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 225-230, 2002.

[37] M. L. McLaughlin, G. Sukhatme, W. Peng, W. Zhu, and J. Parks, “Performance and Co-presence in Heterogeneous Haptic Collaboration,” *Proceedings of IEEE VR 2003*, to appear.

[38] H. Si, “Tetgen: A 3D Delaunay Tetrahedral Mesh Generator.” http://tetgen.berlios.de/

[39] J. Chai, S. Pan, M. X. Zou, and K. Houck, “Context-based Multimodal Input Understanding in Conversational Systems,” *Proceedings of the Fourth IEEE International Conference on Multimodal Interfaces*, 2002.

[40] S. Planalp and K. Knie, “Verbal and Nonverbal Cues to Emotion,” in S. Fussell (Ed.), *The Verbal Communication of Emotions: Interdisciplinary Perspectives*, Lawrence Erlbaum, Mahwah, NJ, pp. 55-77, 2002.

[41] B. O’Keefe, “The Logic of Message Design: Individual Differences in Reasoning about Communication,” *Communication Monographs*, vol. 55, pp. 80-103, 1988.

[42] R. Buck and C. A. VanLear, “Verbal and Nonverbal Communication: Distinguishing Symbolic, Spontaneous, and Pseudo-Spontaneous Nonverbal Behavior,” *Journal of Communication*, vol. 52, pp. 522-541, 2002.

[43] C. Nass and Y. Moon, “Machines and Mindlessness: Social Responses to Computers,” *Journal of Social Issues*, vol 56(1), pp. 81-103, 2000.

[44] C. Nass, Y. Moon, and P. Carney, “Are Respondents Polite to Computers? Social Desirability and Direct Responses to Computers,” *Journal of Applied Social Psychology,* vol. 29(5), pp. 1093-1110, 1999.

[45] B. Reeves and C. Nass, *The Media Equation: How People Treat Computers, Televisions, and New Media Like Real People and Places*, Cambridge University Press, New York, 1996.

[46] C. Kevin, T. Kesavadas, and J. Mayrose, “Development of the Virtual Human Abdomen: Algorithms and Methodologies,” *Proceedings of ACM-SIGGRAPH 2001*, p.170, 2001.

[47] N. Langrana, G. Burdea, J. Ladeiji, and M. Dinsmore, “Human Performance using Virtual Reality Tumor Palpation Simulation,” *Computers and Graphics*, vol. 21(4), pp. 451-458, 1997.

[48] D. D’Aulignac and R. Balaniuk, “Providing Reliable Virtual, Echographic Exam of the Human Thigh,” *Proceedings of the Fourth PHANToM Users Group Workshop*, AI Lab Technical Report No. 1675 and RLE Technical Report No. 633, MIT, Cambridge, MA, 1999.

[49] A. Mor, “5 DOF Force Feedback using the 3 DOF PHANToM and a 2 DOF Device,” *Proceedings of the PHANToM Users Group, PUG98*, 1998.