Three-Dimensional Surface Point Cloud Ultrasound for Better Understanding and Transmission of Ultrasound Scan Information

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Abstract

Ultrasound is notoriously plagued by high user dependence. There is a steep drop-off in information in going from what the sonographer sees during image acquisition and what the interpreting radiologist is able to view at the reading station. One countermeasure is probe localization and tracking. Current implementations are too difficult and expensive to use and/or do not provide adequate detail and perspective. The aim of this work was to demonstrate that a protocol combining surface three-dimensional photographic imaging with traditional ultrasound images may be a solution to the problem of probe localization, this approach being termed surface point cloud ultrasound (SPC-US). Ultrasound images were obtained of major vessels in an ultrasound training phantom, while simultaneously obtaining surface point cloud (SPC) 3D photographic images, with additional scanning performed on the right forearm soft tissues, kidneys, chest, and pelvis. The resulting sets of grayscale/color Doppler ultrasound and SPC images are juxtaposed and displayed for interpretation in a manner analogous to current text-based annotation or computer-generated stick figure probe position illustrations. Clearly demonstrated is that SPC-US better communicates information of probe position and orientation. Overall, it is shown that SPC-US provides much richer image representations of probe position on the patients than the current prevailing schemes. SPC-US turns out to be a rather general technique with many anticipated future applications, though only a few sample applications are illustrated in the present work.

Keywords Point cloud · Three-dimensional surface · Three-dimensional camera · Ultrasound probe position · Ultrasound navigation

Introduction

Ultrasound has well-known advantages compared to other imaging modalities, such as the avoidance of ionizing radiation and low costs relative to CT and MRI. However, some drawbacks of ultrasound are classic and seemingly inherent, principally its heavy user dependence and relatively low exam reproducibility. A large drop-off in information accompanies the transfer of images from the technologist or radiologist who performed the study to the interpreting radiologist at the workstation. Part of the information loss relates to disorientation resulting from (a) obliquely angled imaging planes and (b) the fundamental physics of sound propagation, which limits

evaluation to the interior of a patient's body. In contradistinction, CT and MRI use a standard set of orthogonal imaging planes—axial, sagittal, and coronal—which are easily recognizable. Additionally, CT and MRI have fields of view including not just the patient's body and internal organs but the space immediately outside of the patient's skin surface. Taken together, these factors help to orient an interpreting radiologist reading CT/MRI to the global position of abnormalities within the patient. Ultrasound, lacking these, often can be disorienting with regard to where exactly the abnormality is located in the patient.

To address these issues, much work has been performed on ultrasound probe localization and precise quantification of probe forces [1–3] and using camera-derived information about particular skin features [4, 5], as well as the use of three-dimensional ultrasound [6]. Precise probe localization regarding its six degrees of freedom (probe center of mass x , y , and z as well as the three Euler angles ϕ , θ , and ψ describing any rotation and thus rotational orientation of a rigid body) has long been recognized as desirable for precise probe

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localization, and several methods have been introduced commercially to achieve this positional information, employing optical tracking systems [7–9] as well as external electromagnetic tracking systems [10–12].

The aforementioned classes of ultrasound navigation and position tracking are by definition somewhat complicated, bulky, and therefore time-consuming and difficult to set up and use. Further, ultrasound probe tracking is typically used for CT- or MRI-to-ultrasound co-registration, often for guided biopsies or procedures [8, 13–15]. This is instead of providing easily interpretable information regarding probe and patient body surface for diagnostic ultrasound interpretations. Such information is likely to be increasingly valuable given the high volume of soft tissue lesions requiring individualized probe angles and the increasing use of point-of-care ultrasound, often employing non-standard views in comparison with technologist-performed imaging protocols [16].

Given the current limitations of probe localization, the aim of this work is to propose and introduce a three-dimensional (3D) photography-based imaging protocol to visualize patient + probe during ultrasound scans. 3D photography has found increasing applications in medical diagnostics, with 3D

camera body surface information recently employed in dermatology [17] and urology [18].

In the present work, 3D surface point cloud (SPC) files—which are generated by 3D cameras—and the corresponding SPC images provide a rotatable representation of the patient body surface + probe obtained simultaneously with the corresponding ultrasound grayscale images. Such information can be juxtaposed to provide more rich and informative images than current approaches. This approach and mix of modalities is named surface point cloud ultrasound (SPC-US).

Methods

This study was determined to be exempt from Investigational Review Board approval. 3D camera point cloud files were obtained via the Artec Eva 3D camera (Artec 3D, Santa Clara, CA) using Blue Phantom ultrasound training model phantoms (CAE Healthcare, Sarasota, FL) and both Zonare (Mindray, Mahwah, NJ) and GE Logiq E9 (GE Healthcare, Chicago, IL) ultrasound systems. The basic setup is illustrated in Fig. 1. This particular representation of the process features

Fig. 1 Layout of the SPC-US approach. 3D camera (here, the Microsoft Kinect) held with the left hand is scanning the patient body surface and the ultrasound probe while the phantom patient's neck is being scanned with the right hand to visualize the right carotid artery. Output of the

ultrasound is seen on the monitor on the left. Post-processed corresponding surface point cloud image is displayed in the monitor on the right

a Microsoft Kinect (Microsoft, Redmond, WA) 3D camera instead of the Artec Eva, which was used to generate the SPC-US sample images shown in subsequent figures.

Ultrasound images from the phantom were saved as dicom image files. Scanning the patient + probe with the Artec Eva 3D camera in the same manner as in Fig. 1 generated 3D SPCs, which were saved as OBJ files. By keeping track of the labels in corresponding ultrasound dicom images and 3D SPC images, pairings of ultrasound/SPC images were assigned.

SPC files were post-processed with the open source programs MeshLab (version 2016.12) and Blender (version 2.79). Angle calculations were performed in Blender. All SPC images used in Figs. 2, 3, 4, 5, 6, and 7 were generated from MeshLab using a built-in functionality that saves screen shots as PNG files. To generate Figs. 2 and 3, screenshots of the dicom images were juxtaposed with the corresponding MeshLab screenshots in Microsoft PowerPoint, and both were resized to achieve their relative dimensions. At this point, a screenshot of the juxtaposed images was obtained.

Results

There was successful retrieval of 3D phantom + probe SPC images and simultaneous grayscale/Doppler image acquisition. Hence, paired sets of images—one corresponding to grayscale/Doppler images, the other to the 3D phantom + probe SPC—were obtained. Figure 2 displays the juxtaposed grayscale ultrasound image of the right common carotid artery together with three snapshots of the corresponding 3D SPC, these 2D snapshots having been obtained at

Fig. 2 Grayscale ultrasound image of phantom right common carotid artery along with 2D snapshots of the patient + probe surface point cloud taken at different perspectives. The surface point cloud was obtained at the time the ultrasound image was recorded

difference perspective angles in order to better express the probe orientation with regard to the patient. Figure 3 displays a similar image for the right subclavian vein with color Doppler flow.

Figure 4a–c displays a comparison between SPC-US and the two current standard representations of probe position for a soft tissue ultrasound image of a forearm lesion (since no lesion was present inside of the phantom; the grayscale image is from Halula et al. [19]). Figure 4a, displaying the textual annotation of lesion location, provides only a vague sense of where the patient is being imaged. Figure 4b shows the digital stick figure representation of the patient's right forearm with an L-shaped bar representing the probe. Though this gives an approximate sense of where the patient was imaged, only limited 2D information, and no 3D information, is present. Finally, Fig. 4c shows a snapshot of the phantom forearm + probe SPC. This offers a much more nuanced and informative representation of the exact location of the probe on the patient's forearm. Such information is more reliable than the other two representations, because it is not subject to mistakes of probe position annotation by the sonographer. In a real patient, it in fact would represent the exact 3D probe position on the patient body surface at just the time when the grayscale image is obtained.

Figure 5a–f displays a similar comparison between SPC-US and the two currently prevailing methods, this time to analyze the kidneys (grayscale images obtained from Hansen et al. [20]).

Figures 6a–f and 7a–f highlight a key advantage of SPC-US over textual annotation and stick figure representations, namely that probe orientation/angle in 3D is retained and displayable. Figure 6a–f demonstrates various angles along the probe's minor axis (though not featured here, calculating angle along the probe's major axis is also available). Figure 7a–f shows various angles of the probe's major axis with respect to the patient's spinal or major axis.

Fig. 3 Color Doppler image of the phantom's right subclavian vein with flow turned on. There is a corresponding 2D snapshot of the 3D surface point cloud representation gathered at the time of Doppler image acquisition

Fig. 4 Comparison of different modalities for representing probe position in the case of a right forearm soft tissue mass highlighted by yellow arrows (grayscale image obtained from Halula et al. [19]). **a** Purely textural representation. **b** Digital stick figure arm and L-shaped structure that is meant to represent the probe (obtained from GE Logiq

E9 machine.) **c** Probe position obtained via the surface point cloud ultrasound (SPC-US) approach. Namely, here a surface point cloud 2D snapshot of the ultrasound probe on the phantom arm is displayed alongside the soft tissue mass

Discussion

The classic interrelated problems of user dependence and study variability in ultrasound demand fresh solutions that do not compromise the speed of scanning or unduly burden the technologists or point-of-care physicians obtaining images. 3D photography as demonstrated here in the SPC-US method is a general approach that can add valuable information to a wide variety of ultrasound studies. A few examples and possible uses are demonstrated here.

A key advantage of SPC-US over the current methods of textual annotation and stick figure probe position representation is the rich 3D information showing where exactly the probe is located and at which angles it is oriented. The information obtained from SPC-US can be helpful in longitudinal monitoring of soft tissue lesions or lymph nodes, correlation

of ultrasound findings with physical exam, or as a starting point for ultrasound probe placement for subsequent ultrasound-guided biopsies.

SPC-US leaves no doubt as to patient identity and lesion location, as exemplified in Fig. 5c. Confidence in probe position with SPC-US is complete, and technologist error in entering probe location is essentially eliminated. SPC-US could therefore prove useful in quality control by minimizing so-called never-events of wrong-patient/wrong-side/wrong-site procedures. Juxtaposed images like Fig. 5c can be imagined to serve as checkpoints in preoperative time-outs. This could in a similar manner replace intraoperative ultrasound to ensure correct sidedness of non-palpable testicular tumors just before an orchiectomy. An SPC-US image showing the lesion and the side could be instead displayed as part of the time-out process.

Fig. 5 SPC-US comparison for renal imaging. Again, ultrasound images of the right and left kidney, which were not procurable by the phantom directly, are taken from another paper (Hansen et al. [20]). The right kidney here contains a mass and the left kidney is atrophic and

echogenic. **a, d** Textural representations, **b, e** Stick figure representations (present in the Hansen et al.'s original images). **c, f** Corresponding information via SPC-US with point cloud images obtained from the phantom patient

Fig. 6 Illustration of SPC-US's ability to convey probe angular information. Three probe angles are displayed here on the phantom's thorax. Images on the right show that actual angles along the probe short axis may be calculated and displayed. Though not shown here, angles along the probe long axis can be calculated and displayed in the same manner

Being able to verify the probe orientation during color Doppler vessel imaging can ensure that flow is along a particular direction. For example, this could confirm flow direction in portal vein color Doppler studies, helping to establish hepatopetal versus hepatofugal flow in the setting of cirrhosis.

Accurate knowledge of probe location to accompany ultrasound images may be progressively more important given increasing use of point-of-care ultrasound [16] by non-radiologist/non-technologist clinicians. Surface information is meaningful since such studies often do not follow the standard set of angles and positions that are employed by dedicated technologists with pre-determined standardized imaging protocols, such as the classic abdominal ultrasound examination.

SPC-US could improve training of radiology residents and technologists by allowing for a supervisor or attending radiologist to evaluate not only the grayscale/Doppler image quality but also the technique of acquisition via probe position and which regions were scanned.

Additional information beyond the surface 3D images obtained simultaneously with grayscale/Doppler images could be afforded by storing probe locations corresponding to regions on the body surface that the sonographer scanned even when not recording ultrasound images. This could allow the

interpreting radiologist to know for example whether all cervical lymph node stations were studied in a thyroid ultrasound examination, with the assumption being that if a suspicious lymph node was seen, grayscale images of the node would have been recorded by the technologist.

It is feasible that fused SPC-US images could be co-registered with CT or MRI, so that the direction of the ultrasound imaging beam/field-of-view could be projected into the comparison CT or MRI study. This could provide a sort of retrospective fused image which may be helpful for example in lesion surveillance.

Limitations

Image acquisition as performed in the current study was somewhat cumbersome. The challenge of holding the 3D camera and ultrasound probe separately while simultaneously obtaining grayscale images ultimately necessitated assistance. This would not be ideal for clinical productivity, in which a single technologist or point-of-care clinician typically obtains the studies. Furthermore, in order to obtain high-quality SPCs, a wide range of camera angles is needed. In the current study,

Fig. 7 Illustration of SPC-US's ability to display probe angle relative to patient axis. Here, a set of three angles of probe long axis with respect to patient's spinal axis are displayed, with the actual calculated angles shown on the right-sided images

that meant spending up to a few minutes scanning around the patient for each image. Both of these challenges could in future applications be addressed via multiple 3D cameras mechanically mounted at different locations and angles simultaneously obtaining and merging their data, as has been done clinically recently with impressive speed and resolution for melanoma surveillance.

A fair amount of post-processing was required to generate the figures used in this study. For purposes of display, to generate Figs. 2 and 3, the hand and arm holding the ultrasound probe as well as the power cord connected to the probe were removed in MeshLab from the SPC data before obtaining snapshots. Additional post-processing performed in MeshLab consisted of cleaning up points constituting noise in the data set as well as coloring the different components of the surface (for example, ultrasound probe was colored white and the operator glove was colored blue in the images displayed).

In practice, much if not all post-processing would be unnecessary. Just as well-executed low-dose CT images are relatively grainy yet diagnostic, SPC-US images could be less “pretty” as long as they still contain the key information needed for diagnosis. Regarding color information: this is an

included component of many 3D camera systems and is often present in the SPC data automatically or can be turned off (grayscale surface images) as another option.

Future Direction

Significant advances continue in 3D photography, many of which can address limitations encountered in the current work. As mentioned earlier, a multi-camera approach utilizing mechanical 3D camera mounts at various angles could speed up image acquisition considerably. This is also anticipated to address a core limitation in the current work of needing to hold the 3D camera in one hand while handling the ultrasound probe with the other hand, as shown in Fig. 1. Such a setup would be rather challenging in practice, and would likely distract a sonographer from the crucial process of obtaining the best possible ultrasound images.

Though the Artec Eva used in this study retails for roughly 20,000 USD, cheaper options for 3D point cloud cameras currently exist. It is also anticipated that as 3D camera technology accelerates, costs will decrease overall.

A major challenge that will need to be addressed is how best to store SPC images in a PACS viewer. One approach would be similar to the display style shown in Figs. 2, 3, 4, 5, 6, and 7, that is to place SPC screenshots in a corner of the corresponding ultrasound images and save this combined image as a dicom file for viewing at the PACS workstation. Another potential approach could involve converting an SPC screenshot directly to a dicom file and then including the SPC images as a series in a PACS viewer. Since there would be corresponding ultrasound and SPC dicom images, the two series could be linked to scroll through them simultaneously, similar to how diffusion-weighted and apparent diffusion coefficient images are typically stored as separate series with the same number of images in each series for direct comparison. A third possible method could be to rotate systematically the viewing perspective/angle of the SPC as can be done in MeshLab, obtaining snapshots at each angle and storing all angle screenshots in a dicom series. Then, the user could rotate the patient + probe SPC representations by scrolling through such a series, with the title of the series possibly reflecting the corresponding grayscale ultrasound image for correspondence.

Mobile devices may be an important component of future iterations given that 3D surface time-of-flight information has recently been introduced into mobile devices. Likewise, there are now ultrasound devices that connect to and display images on mobile devices, for example in the Butterfly iQ (Butterfly, Guilford, CT). Hence, it may make sense to integrate both functions of SPC-US into smart phones or tablets.

Conclusions

As ultrasound use grows particularly in point-of-care clinical applications, it is vital to ameliorate some of its classic shortcomings, namely user dependence and lack of reproducibility. Prior approaches to this have proven expensive, cumbersome, non-intuitive, and focused on fusion with CT or MRI for the purposes of biopsy or treatment.

In this work, the use of 3D surface images to accompany ultrasound images is proposed and demonstrated as proof-of-principle. The approach is named surface point cloud ultrasound (SPC-US). Demonstration images illustrate some major advantages of SPC-US over the current predominating textural probe position annotation and digital stick figure representations. Foremost among these advantages is an exact and rotatable 3D representation of exact probe position on the patient while being scanned. Advances in quality assurance and quality control are additional features. SPC-US is a very general approach/add-on to ultrasound that brings information about the “outside” (patient and probe surface) to bear on sonographic information about the patient’s “inside” (tissues and organs). It is thus anticipated that future applications not considered here will be found for SPC-US.

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References

1. Harris-Love MO, Ismail C, Monfaredi R, Hernandez HJ, Pennington D, Woletz P et al.: Interrater reliability of quantitative ultrasound using force feedback among examiners with varied levels of experience. *PeerJ*. 4:e2146, 2016
2. Dhyani M, Roll SC, Gilbertson MW, Orlowski M, Anvari A, Li Q et al.: A pilot study to precisely quantify forces applied by sonographers while scanning: a step toward reducing ergonomic injury. *Work*. 58(2):241–247, 2017
3. Gilbertson MW, Anthony BW: An ergonomic, instrumented ultrasound probe for 6-axis force/torque measurement. *Conf Proc IEEE Eng Med Biol Soc*. 2013:140–143, 2013
4. Du X, Anthony B: Controlled angular and radial scanning for super resolution concentric circular imaging. *Opt Express*. 24(20):22581–22595, 2016
5. Sun SY, Gilbertson M, Anthony BW: Probe localization for free-hand 3D ultrasound by tracking skin features. *Med Image Comput Comput Assist Interv*. 17(Pt 2):365–372, 2014
6. Xiang Z, Fincke J, Kuzmin A, Lempitsky V, Anthony B: A single element 3D ultrasound tomography system. *Conf Proc IEEE Eng Med Biol Soc*. 2015:5541–5544, 2015
7. Beller S, Hunerbein M, Eulenstein S, Lange T, Schlag PM: Feasibility of navigated resection of liver tumors using multiplanar visualization of intraoperative 3-dimensional ultrasound data. *Ann Surg*. 246(2):288–294, 2007
8. Kucukkaya F, Aribal E, Tureli D, Altas H, Kaya H: Use of a volume navigation technique for combining real-time ultrasound and contrast-enhanced MRI: accuracy and feasibility of a novel technique for locating breast lesions. *AJR Am J Roentgenol*. 206(1): 217–225, 2016
9. Muns A, Meixensberger J, Arnold S, Schmitgen A, Arlt F, Chalopin C et al.: Integration of a 3D ultrasound probe into neuronavigation. *Acta Neurochir (Wien)*. 153(7):1529–1533, 2011
10. Putzer D, Arco D, Schamberger B, Schanda F, Mahlkecht J, Widmann G et al.: Comparison of two electromagnetic navigation systems for CT-guided punctures: a phantom study. *Rofo*. 188(5): 470–478, 2016
11. Joh JH, Han SA, Kim SH, Park HC: Ultrasound fusion imaging with real-time navigation for the surveillance after endovascular aortic aneurysm repair. *Ann Surg*. 92(6):436–439, 2017
12. Ma L, Nakamae K, Wang J, Kiyomatsu H, Tsukihara H, Kobayashi E et al.: Image-guided laparoscopic pelvic lymph node dissection using stereo visual tracking free-hand laparoscopic ultrasound. *Conf Proc IEEE Eng Med Biol Soc*. 2017:3240–3243, 2017
13. Ungi T, Moul E, Schwab JH, Fichtinger G: Tracked ultrasound snapshots in percutaneous pedicle screw placement navigation: a feasibility study. *Clin Orthop Relat Res*. 471(12):4047–4055, 2013
14. Takamoto T, Mise Y, Satou S, Kobayashi Y, Miura K, Saiura A et al.: Feasibility of intraoperative navigation for liver resection using real-time virtual sonography with novel automatic registration system. *World J Surg*., 2017
15. Doba N, Fukuda H, Numata K, Hao Y, Hara K, Nozaki A et al.: A new device for fiducial registration of image-guided navigation system for liver RFA. *Int J Comput Assist Radiol Surg*., 2017
16. Marin JR, Lewiss RE, American Academy of Pediatrics CoPEM, Society for Academic Emergency Medicine AoEU, American

- College of Emergency Physicians PEMC, World Interactive Network Focused on Critical U: Point-of-care ultrasonography by pediatric emergency medicine physicians. *Pediatrics*. 135(4): e1113–e1122, 2015
17. Chung E, Marchetti MA, Scope A, Dusza SW, Fonseca M, DaSilva D et al.: Towards three-dimensional temporal monitoring of naevi: a comparison of methodologies for assessing longitudinal changes in skin surface area around naevi. *Br J Dermatol*. 175(6):1376–1378, 2016
 18. Margolin EJ, Mlynarczyk CM, Mulhall JP, Stember DS, Stahl PJ: Three-dimensional photography for quantitative assessment of penile volume-loss deformities in Peyronie's disease. *J Sex Med*. 14(6):829–833, 2017
 19. Halula SE, Leino DG, Patel MN, Racadio JM, Lungren MP: Isolated upper extremity posttransplant lymphoproliferative disorder in a child. *Case Rep Radiol*. 2015:813989, 2015
 20. Hansen KL, Nielsen MB, Ewertsen C: Ultrasonography of the kidney: a pictorial review. *Diagnostics (Basel)*. 6(1), 2015