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Advanced Computer Integrated Surgery

March 6, 2017

Seminar Write-Up

Ultrasound imaging (US) is a popular imaging modality because of its ability to image deep into the body without the use of ionizing radiation. Photoacoustic (PA) imaging also uses no ionizing radiation, but it has the added ability to more distinctly image critical structures such as nerves and blood vessels, structures that do not even show up in traditional radiation-based modalities such as X-Ray and CT without the use of a contrast agent. The trade-off is that PA Imaging has a lower imaging depth. When combined, this pair of modalities has the potential to be a powerful intraoperative imaging tool.   
 However, there is even greater potential when combining US and PA Imaging with a force-controlled robot. Due to their traits of high resolution and no radiation, they could potentially be used to automate simple diagnostic and surgical procedures. As explored by Risto Kojcev et al[1], Ultrasound image-guided needle insertions can be completed with high precision. In this study, two KUKA iiwa robots, one equipped with an ultrasound probe and the other equipped with a needle, were tasked with navigating the needle to a target visualized by the ultrasound probe. The procedure involved three main steps: (1) Preoperative calibration and registration of the robots and their RGB-D cameras (2) Ultrasound volume acquisition and processing and (3) US guided needle insertion. The calibration involved pivot calibration for the needle-to-robot registration, hand-eye calibration for the RGBD camera-to-robot registration and Checkerboard calibration for the robot1-to-robot2 registration. After calibration, one of the robots scans the patient’s surface with its camera, and a physician selects a ROI by drawing a rectangle on a visualization of the patient’s surface. Then, the ultrasound probe robot performs an autonomous scan of the ROI on the patient. The gathered images are compounded and the resulting volume is used to register preoperative data, such as a CT or MRI, to the patient. After registration, the ultrasound probe moves to visualize the ROI as identified in the preoperative data. Once all these steps are completed the needle is inserted through the line defined by the intersection of the patient’s surface and the ultrasound image plane.

The procedure was performed with two different phantoms, water and gel, at two entry angles, 30 and 45 degrees, and at 3 different speeds, 1, 3, and 5 mm/s. In general the error, measured as the distance between the needle tip and the desired location in the B-mode image, was around 1 mm. The accuracy results are good. However there are several limitations to this set-up. The first is the assumption that you can always insert the needle directly into the FOV of the ultrasound probe. For some procedures and patient types this is a valid enough assumption but for targets near critical structures such as arteries or for obese patients whose ultrasound images are cluttered this system could fail. In particular, if the patient is obese, registering to a preoperative CT or MRI using a compounded B-mode volume would likely not be accurate. Adopting a beamforming method that minimizes this clutter, such as Short Lag Spatial Coherence beamforming [2] could remediate this problem. Additionally, the tracking of the needle in the US image during the insertion could be simplified if PA imaging was done. The needle tip would appear as a point source in the image if the inserted needle was filled with an optical fiber. This simplifies the needle tracking from the complicated RANSAC, Kalman filtering, and polynomial fitting system as reported to simple intensity thresholding.

A place where this kind of technology can have a large impact is in extreme and remote environments, where it is not easy or possible to bring medical doctors. In particular, autonomous medical robots can have their biggest impact in manned deep space missions. The constraints of spaceflight, including sensitive equipment and large amounts of ambient cosmic radiation, render traditional diagnostic imaging modalities such as CT, X-Ray and MRI impractical or ineffective. These constraints substantially increase the attractiveness of US and perhaps PA imaging due to their compact size and zero radiation dose. Long term spaceflight has also been shown to have many degenerative effects on astronauts, including atherosclerosis, tumors, and nerve degradation due to ambient radiation as well as eye deformation and thus vision impairment due to increased brain pressure. For these reasons NASA has conducted studies into the efficacy of Ultrasound as an intraflight diagnostic tool. In fact, a laptop-sized Ultrasound machine is the only diagnostic imaging device available on the International Space Station. Martin et Al [3] explored the ability of ‘astonaut-like’ individuals with zero Ultrasound experience to capture diagnostic quality images with just-in-time training provided by video glasses worn during the procedure. In this study, two groups of 10 ‘astronaut-like’ participants, where ‘astronaut-like’ is defined as having a college a degree and in reasonable health, were recruited to take images of the carotid artery and the eye. Pairs of two would take turns acting as operator and patient. The operator, who has no previous experience, would watch a demonstrative video on their video glasses and attempt to acquire a diagnostic quality image. There was no time limit imposed on the operator. The carotid images were scored as either ‘adequate’ or ‘not adequate’ by experts, while the ophthalmic images were scored on a scale of 1-10 with images rated 4 or higher being considered adequate. For the carotid images, 8 out of 10 were deemed ‘adequate’ and the ophthalmic images received a mean score of 6.8. All trials were completed in less than 30 minutes.

At first glance these results might seem to imply that astronauts could obtain quality images with a well prepared training video. However, as recognized by the authors, this experiment is not realistic. Some issues that were not addressed include: (1) the study was not performed in space (2) the participants were not physically or mentally fatigued like an astronaut would be (3) they had unlimited time to obtain the images, which is not practical in an emergency (4) the microgravity of space makes obtaining force-controlled images for longitudinal analysis impossible (this is a difficult feat even for an experienced sonographer on Earth). This last limitation is likely the most important for extended duration missions, as atherosclerosis and tumors develop over long periods of time and it is extremely important to be able to track their development over time. The system I am developing for Spinal fusions and other spinal procedures would also be able to handle this problem. Autonomous, patient-specific probe placement and scanning with force control is ideal for the collection of longitudinal diagnostic-quality Ultrasound that could make or break a long term deep space mission. Once a tumor or other target is identified using this longitudinal data, a system similar to one presented above, namely another robot with a needle or similar tool, could excise or eliminate the target.

Overall there is great potential to benefit patients with autonomous, robotic medical procedures, even those on Earth. A recent ex vivo study demonstrated the ability of an autonomous robot to produce stronger sutures than a human surgeon (albeit with a few caveats) [4]. Additionally research has been done into having robots ‘learn’ to perform discrete surgical tasks using Deep Learning with the aim of having the robot perform the task autonomously [5]. It will be interesting to see what results when all of these disjoint pieces inevitably find their way into one complete system, and whether it will get anywhere close to the distant goal of an autonomous general surgery robot.

References

[1] Kojcev, Risto, Bernhard Fuerst, Oliver Zettinig, Javad Fotouhi, Sing Chun Lee, Benjamin Frisch, Russell Taylor, Edoardo Sinibaldi, and Nassir Navab. "Dual-robot ultrasound-guided needle placement: closing the planning-imaging-action loop." *International journal of computer assisted radiology and surgery* 11, no. 6 (2016): 1173-1181.

[2] Martin, David S., Timothy L. Caine, Timothy Matz, Stuart Lee, Michael B. Stenger, Ashot E. Sargsyan, and Steven H. Platts. "Virtual guidance as a tool to obtain diagnostic ultrasound for spaceflight and remote environments." *Aviation, space, and environmental medicine* 83, no. 10 (2012): 995-1000.

[3] Lediju, Muyinatu A., Gregg E. Trahey, Brett C. Byram, and Jeremy J. Dahl. "Short-lag spatial coherence of backscattered echoes: Imaging characteristics." IEEE transactions on ultrasonics, ferroelectrics, and frequency control 58, no. 7 (2011).

[4] Shademan, Azad, Ryan S. Decker, Justin D. Opfermann, Simon Leonard, Axel Krieger, and Peter CW Kim. "Supervised autonomous robotic soft tissue surgery." *Science translational medicine* 8, no. 337 (2016): 337ra64-337ra64.

[5] Chow, Der-Lin, Russell C. Jackson, M. Cenk Çavuşoğlu, and Wyatt Newman. "A novel vision guided knot-tying method for autonomous robotic surgery." In *Automation Science and Engineering (CASE),* 2014 IEEE International Conference on, pp. 504-508. IEEE, 2014.